Tampere University

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Modelling and Simulation Design of Power System Protection Laboratory

Master of Science Thesis

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ABSTRACT

RAJ KUMAR: Modelling and Simulation Design of Power System Protection Laboratory
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This thesis work represents the simulation modelling of laboratory environment equipped with all the major power system equipment including generator, motor, transformer and load. The whole system is divided into two separate networks, the power system network and the protection network. The power system network is developed on simulation software and protection network system is designed using the protection relays in hardware. The protection system is designed to protect every equipment individually and in a complex network system.

All the equipment of power system such as motor, generator, transformer and loads developed using simulations are analysed in normal condition and abnormal conditions. Abnormal conditions are produced intentionally on the simulated network to get the disturbances data. The disturbance data obtained from simulation networks are stored and later used for testing. The disturbances produced in modelling are converted to the format of real disturbance data and loaded in the testing device (Omicron). A real laboratory module is made using all important protection relays to provide every equipment with a fully protected environment. The protection relays are configured with setting according to the simulated network parameters and then the disturbances are injected to see the relays operation time, speed, sensitivity, selectivity, reliability and operational behaviours.

This laboratory module will be used for training the customers and partners, its major application is to test a variety of future application which can be created on software and analysed on protection module. During the thesis time period, two real cases were analysed on the protection module and used a similar methodology of thesis work to validate the results. Creating disturbances on a real system is quite difficult and hazardous for equipment to perform in a controllable manner without any damage or wear tear of life expectancy. Secondly, the applications of the network system are so large in number that it’s impossible to build every separate hardware system for testing. But it’s easy to make systems model with software as the equipment parameters can be changed easily without any cost. For designing the protection system, the modelled network and disturbance data is enough to produce more productive solutions.

Keywords: power system, simulation modelling, protection system, disturbances recording, testing & commissioning.

PREFACE

I'm writing this thesis entitled as" *Modelling & Simulation Design of Power System Protection Laboratory*" in order to comply with the university requirements to complete my MSc degree in Smart Grid (Electrical Engineering) from Tampere University of Technology in the year 2019.

The total time period for completing the master's thesis project was from 2nd May to 5th of November 2019. This master thesis project was carried out with the support of Arcteq Relays Oy, a protection relays manufacturing company located in the city of Vaasa, Finland.

I am greatly thankful to Arcteq relays CEO Mr. Juha Arvola for offering me an opportunity to work in collaboration with research and development team, especial thanks to my supervisors Mr. Jani Vainionpää (Senior Application Engineer) and Mr. Tero Virtala (Product Manager), who were extremely supportive throughout my research work. I am thankful to my thesis supervisor Professor Pekka Verho from Tampere University of technology for his guidance and supervision to achieve my goals. I would like thank Mr. Joni Leppilahti (customer service manager) for his help, assistance and guidance at every stage of my work. Finally, I am pleased to show gratitude to my family, colleagues and friends for their unconditional love and inspiration at every moments of life.

Tampere, 5th November 2019

Raj Kumar

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LIST OF FIGURES

ABBREVIATIONS

ANSI	American National Standards Institute
CB	Circuit breaker
CBFP	Circuit breaker failure protection
CT	Current transformer
COMTRADE	Common format for Transient Data Exchange for power systems
EMTP	Electro Magnetic Transients Program
EMC	Electromagnetic compatibility
FFT	Fast Fourier Transform
HMI	Human machine interface
HW	Hardware
IED	Intelligent electronic device
IEEE	Institute of Electrical and Electronics Engineers
OH	Over head
PG&E	Pacific gas and electric company, San Francisco US.
RMS	Root mean square
SLD	Single line diagram
SW	Software
TMS	TMS Time multiplier setting
TNB	TNB Tenaga Nasional Berhad (Utility company in Malaysia)
UG	Underground
VT	Voltage Transformer

ANSI NUMBERS

21	Distance
24	Volts-per-Hertz overexcitation protection V/Hz
25	Synchro-check
27	Undervoltage
32	Power protection
32R	Reverse Power
40	Under excitation
46	Current unbalance
49M	Machine thermal overload
50	Instantaneous overcurrent
50H/51H/68H	Harmonic overcurrent
50BF	Circuit breaker failure protection CBFP
51	AC Inverse Time Overcurrent
52	AC Circuit Breaker
55	Power factor
59	Over voltage
59N	Neutral voltage
59P/27P/47	Sequence voltage
60	Fuse failure
67	AC Directional Overcurrent
87	Differential Protection
87N	Restricted earth fault / cable end differential
81O & 81U	Over frequency & Under frequency
81R	Rate-of-change of frequency

1. INTRODUCTION OF THESIS WORK

Electricity is the need of life and it is impossible to live without it. In the modern world as things are getting modernised, almost every single activity involves the use of electricity. With such huge usage, it is important to look for its reliability and availability in crucial moments. The reliability can only be possible with the good protection equipment installed from generation to the end user customers to confirm the power delivery. The protective equipment senses the faults, then takes an action to cut off power supply by performing a circuit breaker operation and isolates the faulty portion in fraction of seconds to save the rest of the system from a bigger damage or a cascaded power blackout.

As the technology is developing every day, there are lot of developments happening in the power sector due to power production from renewable energy resources and making the electrical networks extremely complex. For more complex networks, complex protection systems will be needed to protect it. Protection devices especially relays are getting innovative to keep pace with complicated network topologies. In past with the traditional networks, the design of the system was radial and power flow was in one direction with limited nodes, but nowadays the power flows in bilateral direction with large number of interconnected nodes. Now, even bilateral power flow is considered as the simplest part of smart grid technology.

With the smart grid, the electrical power networks will be complex with distributed generations like solar and wind, smart metering and smart loads. The system condition monitoring, real time power flow and devices communication will be essential to control such networks. In order to control and monitor such networks, advanced technologies in the field of protection and Information technology are needed at this stage.

For the protection experts with the academic knowledge in protection field and developed technology, need to be trained with the future challenges to make the most effective solutions. In order to bring the theoretical knowledge and practical work on a common page, Arcteq Relays Oy plays an important role to design a protection laboratory for customers trainings and protection experts to make most of it. Developing a laboratory environment to test current protection functions and develop them to more advanced level to cope with future technology [1].

1.1 Motivation of Thesis

The motivation for the thesis work is to gain deeper knowledge and understanding of power system protection especially on generators, motors, transmission lines and loads on normal as well as abnormal conditions. It is also important to understand the types of protection equipment and functionalities needed to protect power system equipment individually or in combination with other system equipment. In order to visualise the normal and abnormal system behaviour, PSCAD software has been used to simulate and analyse the system. After simulation, it is possible to analyse different parameters of power system and its behaviour at different conditions. The real motivation behind the thesis work is to create a system using software and using almost similar parameters as the real systems, then visualize each characteristics of the network on variable conditions. This will help to understand the system characteristics and various parameters to the customers and partners on simulation-based results which can be tested by injecting it in real protective equipment to realize the importance and necessity of protection system and its accurate operation.

There are the following advantages that motivates to perform system modelling.

- Using simulation technology, it is easy to change the power system layout and the size of equipment's according to the applications, which is quite difficult in real system and need extra cost.
- Customers will be able to see the system parameters on normal and abnormal situations.
- It is quite complex to create a disturbance on a system in controlled manner and possibility to damage the system, but in simulation modelling it is possible to achieve it.
- It is always considered easier to simulate the system before doing the real commissioning to get clear picture of the system beforehand.
- Protection designing will be much easier if one has the complete knowledge of faults behaviour already known.
- Relays protection configuration as well as relay protection functions behaviour can be tested by creating a fault though a testing device to check the reliability of protection scheme.
- Simulation models will be helpful for the students and young professional to analyses the systems and provide best solutions for it.

1.2 Objectives of Thesis

The availability of electricity is important in today's fast-moving life where everything is dependent on it. A short interruption me leads to a very disturbing situation for the users due to its critical application like electric controlled doors, lifts, stairs and many more application. So, its demanding to keep the reliability of the system, which can only be achieved by implementing good protection system.

With the development in the networks and applications, the power system is getting more and more complex and need extra attention to the protection devices. Normally, the protection relays are tested by using test equipment's (like Sverker/Programma /Freija /Omicron) that injects fault currents and voltages to the test unit relay and the responses are recorded according to the settings done in the relay. In this thesis work, a complete disturbance with all the parameters will be injected in the protection devices (Relays) using advance technology. The Arcteq Relays Oy is planning to build a laboratory environment to test the protective relays on real power system equipment. In order to build the laboratory model, it is important to make a simulation model of the laboratory environment on a software (PSCAD) to analyse and validate the results. The scope of this thesis work is the modelling of the laboratory with simulation software according to the company requirements and designing a hardware protection module. The future work would be the commissioning of the laboratory with power system equipment which are simulated here.

The Objective of the thesis work include following tasks.

- Basic knowledge of protection system
- Type of protections and protection requirements
- Familiarity with the different types of Relays
- Study of the PSCAD software and modelling techniques
- Laboratory model design layout
- Modelling of the laboratory using PSCAD software
- Faults study and system behaviours
- Construction of protection system module
- Relays configuration, testing and commissioning
- Testing of simulated model disturbances over relay module
- Protection schemes proposal for the laboratory system
- Implementation of Arc protection for laboratory system
- Real case application testing
- Future work and challenges

1.3 Software Implementation

To do the modelling work, following software's are being used, PSCAD is used as the main software for system design & modelling, Corel draw, Inkscape and Paint are used for designing pictures, graph, flowcharts and protection line diagrams.

1.3.1 PSCAD Software

We know that the power system is expanding and getting complex every day, so it's important to have advancement in the tools used for building and simulating models to study the complex system on software's likes PSCAD. This program is developed in the Manitoba HVDC Research Centre. The primary solution engine is known as EMTDC. EMTDC stands for Electromagnetic Transients including DC, and the graphical user interface (GUI) is named as PSCAD [2].

There are many basic models such as 3 phase voltage sources, synchronous generators, induction motors, transmission lines, loads and measuring equipment's which are build up in the PSCAD library. COMTRADE is an important format of the disturbance that is of my project interest to use it in real system purpose.

RTP/COMTRADE Recorder:

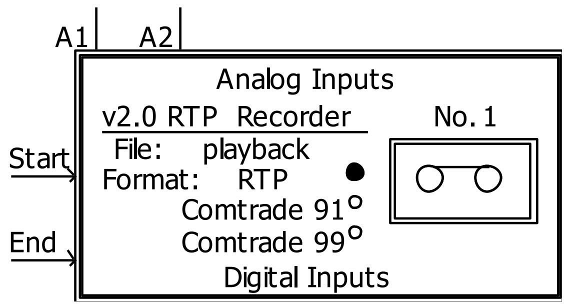


Figure 1.1: Comtrade disturbance recorder

This is a recorder which is used to record up to 28 signals during single simulation. The recording can be done in real time playback (RTP), Comtrade-91 & Comtrade-99, where the Comtrade stands for (Common format for Transient Data Exchange). There are 12 analog input channels and 16 digital input channels. Start and End for recording time slot when it should start and ends the recordings during simulation. In this project work, Comtrade-99 is used as this file is compatible with the use of Omicron testing device.

1.4 Comparison with similar technologies

Almost all the testing laboratories are moving from more software use then the hardware since the alteration or changes are easily done with software in comparison with hardware's. Software technology is growing in every field and implemented in most of application.

Protection relays manufacturing companies are using similar type of techniques to test and validate the protection devices on available application and develop new products for future application using software techniques or combination of software and hardware modules. In order to test certain applications, certain conditions are required and it's very difficult to produce such conditions with hardware or some time impossible to do it. Using software, it is possible to make any condition desired for testing.

1.4.1 RTDS Technologies

The RTDS technology allowed utilities, manufacturers, researchers and educational institutions to test multiple devices with the simulated network while easily adjusting network parameters, contingency scenarios and device settings. It helps the user to validate the performance of protection schemes, digital simulation allows protection equipment to be subjected to virtually all possible faults and operating conditions in a controlled environment. The simulation runs in real time and protective devices can be physically interfaced to the simulated network. This can be used for development and pre-commissioning of protection schemes for utilities, testing the combination of hardware and software made relay models. Also testing novel protection algorithms in real time, prior to target hardware availability and factory testing of protective relays [3].

This thesis work used similar techniques on a smaller scale dedicated for the Arcteq Relays customers and applications by designing a laboratory environment to perform tests using both software and hardware. For all the applications, the simulated networks are created and tested on the simulated relays or hardware relays and results are validated before sending the devices to be used in real applications. This gives a confident to end user as well as good reputation for the manufacturer to sort out complexities and reduces the risks of failure.

1.5 Thesis Outline

Chapter-1 includes, introduction about the project work, motivations to do it and objectives behind the development of thesis work. It also includes the software implementation in thesis work.

Chapter-2 provides a brief introduction about the protection importance, what are the basic requirements needed for the protection system and short explanation about the protection equipment's such as current transformer (CT), voltage transformer (VT), breaker and relays. Basic diagrams of protection equipment connections mounted with the network system.

Chapter-3 explains the modelling methodology and workflow to obtain the main laboratory model. It starts with the design proposal for the laboratory and desired protections. Each unit such as induction motor is designed with speed controls and synchronous generator modelled with the controller individually. Finally, all individual units are combined to get the desired laboratory model.

Chapter-4 deals with the study of disturbance on power system and system behaviours. All the models developed in chapter-3 are applied with the set of disturbances to analysed system behaviour before, after and during faulty conditions. All the disturbances curves recorded and converted to COMTRADE (common mode for transient data exchange) format.

Chapter-5 majorly comprise of the protection module design and installation. Every unit is provided with dedicated protection such as under/over voltages, over currents and under/over frequency protections. One simple dedicated arc protection is also designed for the laboratory.

Chapter-6 explain the process of the commissioning, testing and results validation of the laboratory module using test equipment. Basic understanding of the protective devices configuration settings and use of disturbance analysing software. Two real system applications, one from the relays side and other from arc protection side are tested and analysed.

Chapter-6 is about the conclusions, what has been achieved in thesis work and what are the future goals to develop it more advanced.

2. PROTECTION SYSTEM

2.1 Importance of protection system

The electric power system plays a vital role to produce power from power plants according to the customers load demand, transmit the generated power on the transmission lines by step-up transformers to gain higher voltages and finally distribute to its end customers with in safe, reliable and efficient way. In order to achieve this, it is important that the system should be well protected to perform such operation. Since faults are natural and inevitable, but it's important to make a system able to bear the faults in a protected environment, so that there should be no or minimum loss with little repairing cost. The most important duty of the protection system is the safety of personals and then the safety of equipment's. In order to bring high level of reliability, it is essential to keep system running and free from interruptions, which can be achieve in two ways.

First way is to make a system with very expensive and highly reliable equipment's which has almost zero or minimum maintenance. But this is possible with very small units and for larger units it will be uneconomical. Secondly, design loop network so that on the occurrence of faults, only the small portion is isolated where the fault happens whereas the rest of the system remain unaffected by back feeding from other source. Such conditions can only be achieved by introducing right protection system [4]. The basic protection diagram with CT, VT and a relay is shown in figure 2.1,

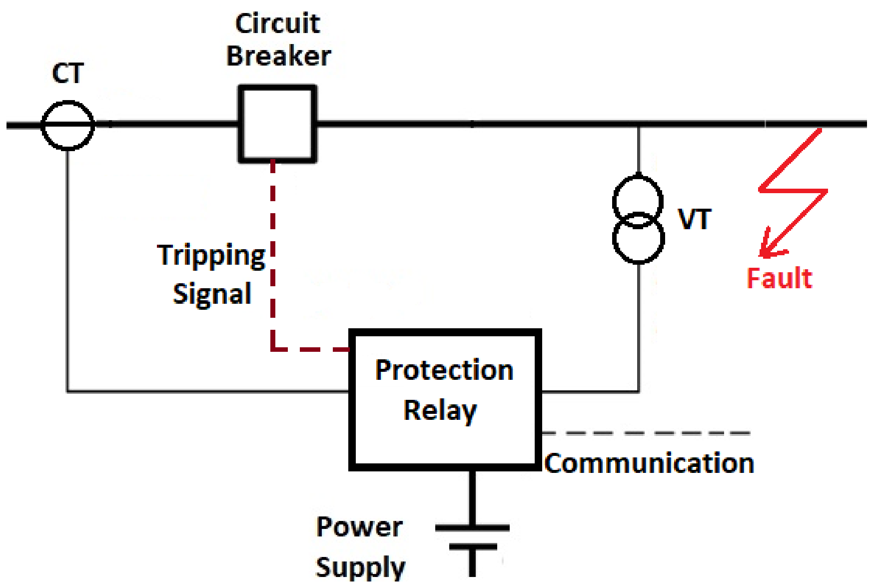


Figure 2.1 Basic protection system [5]

2.2 Basic requirements

Protection system should have the following basic requirements,

1. Power supply continuity
2. Minimum Damage in case of faults
3. Humans Safety.

In order to fulfil the basic requirements, the system need following qualities

- *Selectivity:* the system must be capable to difference between healthy and unhealthy system.
- *Sensitivity:* the system must be sensitive to very small disturbance.
- *Stability:* the system should remain stable after isolating the disturbances.
- *Reliability:* the system should be reliable, and protections must operate when desired.
- *Speed:* The faster the speed, minimum the damage to the system, so it is expected for the protection system to operate with high speed.
- *Security*: System must be secure and should not be affected by nearby devices operation. Secure communication protocols when operating remotely. [5].

2.3 Components

There is a variety of equipment's used for the implementation of protection system. Following are the basic equipment's must be needed in the system.

2.3.1 Circuit Breakers (CB)

The device used to connect and disconnect network parts into and from the system, it performs ON/OFF operations during normal as well as faulty conditions after getting command from the relay is known as circuit breaker. It performs a critical role as the part of the network and bears few cycles of fault current through it and waits for the command/signal from the relay. The circuit breaker breaks the flowing current in the natural zero crossing of sinusoidal signal. Typical modern circuit breaker operating time is below 40ms from the open command given to it. The breaker is composed of tripping coil, latching mechanism, main and auxiliary contacts.

Circuit breaker tripping takes place in following steps,

At first, Relay devices senses the fault condition on the basis of data received form measuring devices connected with the circuit, then it makes a contact to energize the tripping coil of circuit breaker, as the trip coil energizes, it trips the circuit breaker by opening the make contact and isolates the circuit. Finally, the trip coil is de-energized by opening the auxiliary contacts of circuit breakers. This process takes few of milliseconds depends upon the relays and breaker operation time. It is important to perform all events as fast as possible and time describes as the tripping time of circuit breaker. The time phenomenon can be easily understood in the following figure 2.2 [4].

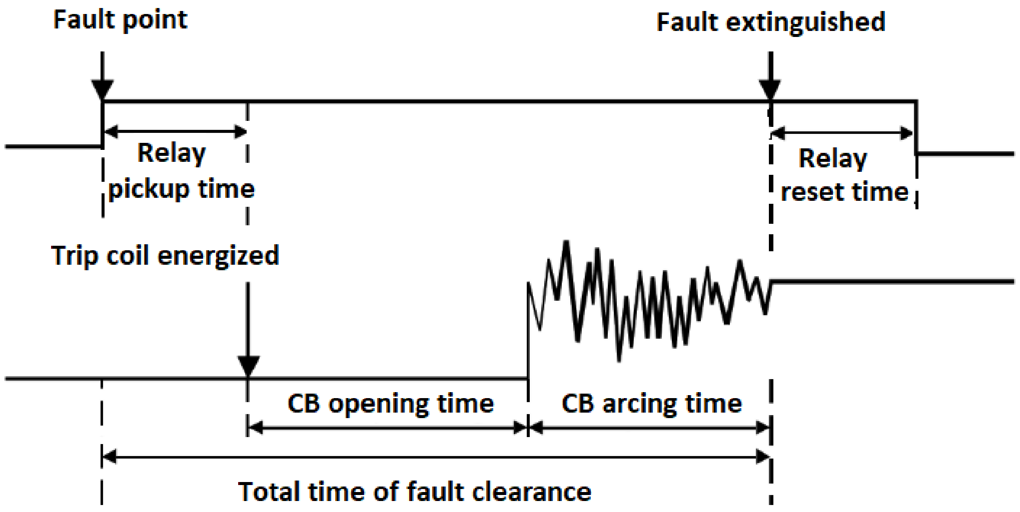


Figure 2.2: fault clearance curve [4]

There are different types of circuit breakers being used in the system and the breaker type is based on quenching medium used in the breakers such as air, oil, vacuum and sulphuric hexafluoride (SF6).

2.3.2 Relays

This device is the brain of the network, which performs operations by giving commands to the circuit breaker or creating alarms to the operator by comparing the real time measurements of the network with the settings set inside the programmed relay. It receives data from measuring equipment's, convert it into desired data signal, compare it with the standard settings and then take actions accordingly by creating an alarm for the operator or a trip signal to the breakers. Relay are defined by the IEEE as "an electronic device made to break the source when it faces a desired condition to control the electrical circuit'' [6]. The relays history starts with the electromechanical type, which later replaced by solid state devices. Now a day's digital microprocessor-based relays are being used due to its best performance. The flowchart and basic general diagram of protection IED is shown here,

Following flowchart gives a basic arrangement of protection functions. It is comprised of analog measurements and its comparison with the pick-up values and operating time characteristics. The timer in milliseconds shows the cycle operation time of each tasks as seen in the figure 2.3 given here,

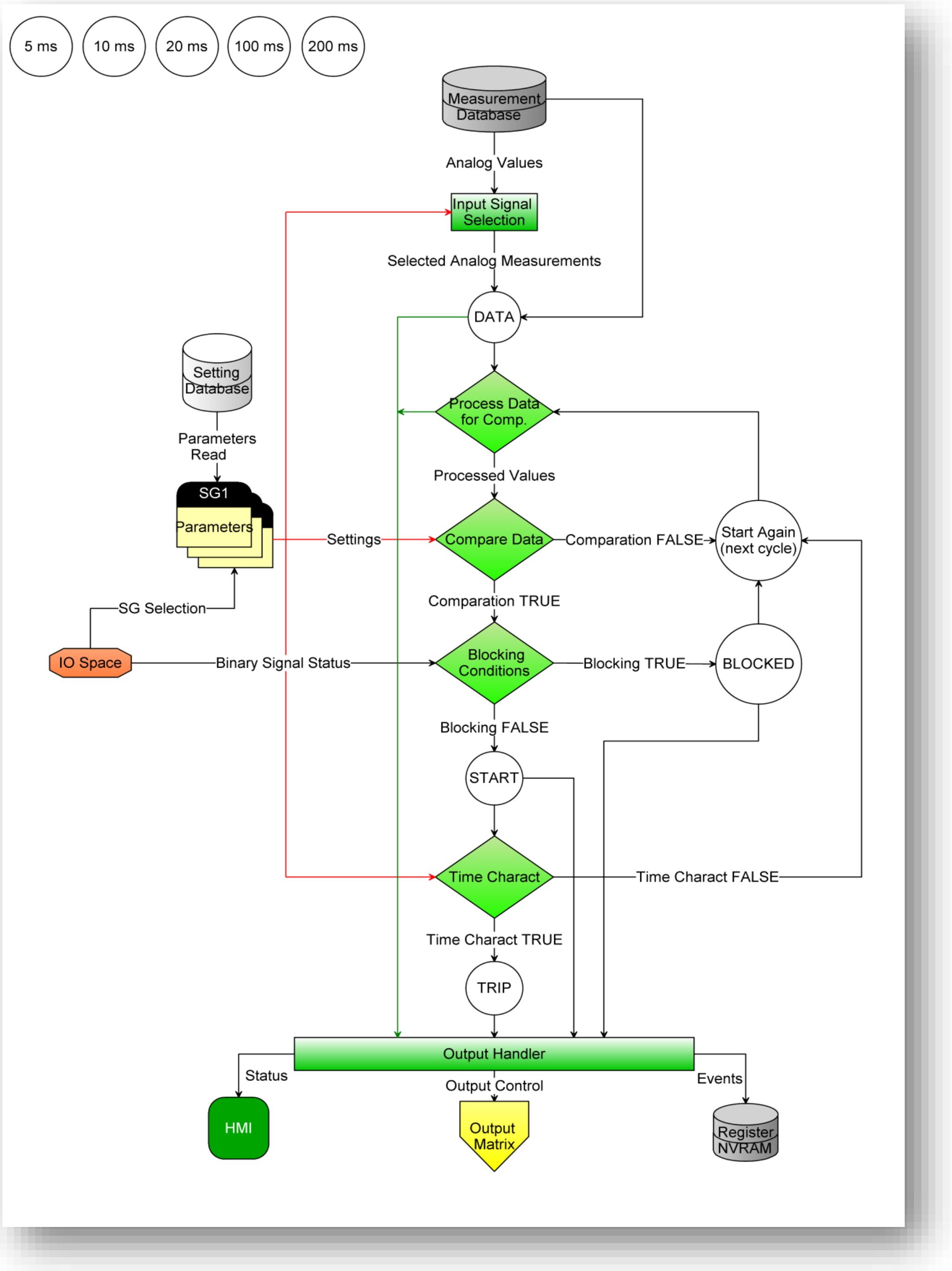


Figure 2.3: Relay operations flowchart [6]

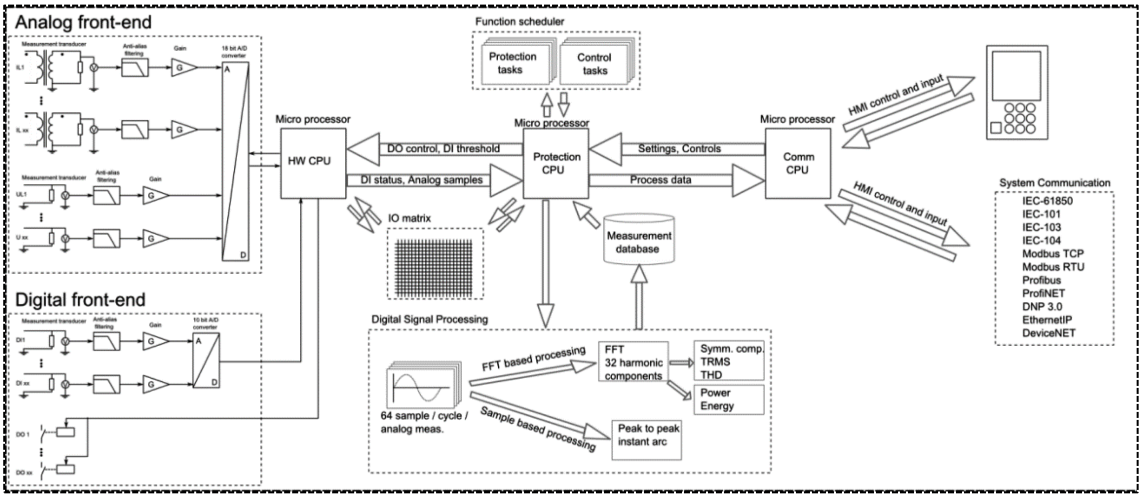


Figure 2.4: Relay internal circuit [6]

2.3.3 Fuses

The very basic equipment developed when the protection came into existence. This device used for the single time only and a self-destructive equipment that burns itself to secure the network. This equipment doesn’t require any external control like the circuit breaker, so it operates independently to detect and react all alone.

All fuses have the inverse current characteristics, which means that they withstand perfectly under normal current with in limit and as the current goes above the nominal current value, the fuse will operate. As the current goes higher the withstand time reduces, higher the magnitude of current, lesser time needed for fuse to blow. The fuse characteristics curve can be observed in figure 2.5 given below. The selection of fuses get complex with loads which draw higher amount of inrush current at the start such as induction motors where it becomes impossible for the fuse to distinguish between the fault and inrush current, and higher possible value of fuse to pass inrush current may lead to the missing of faulty situations.

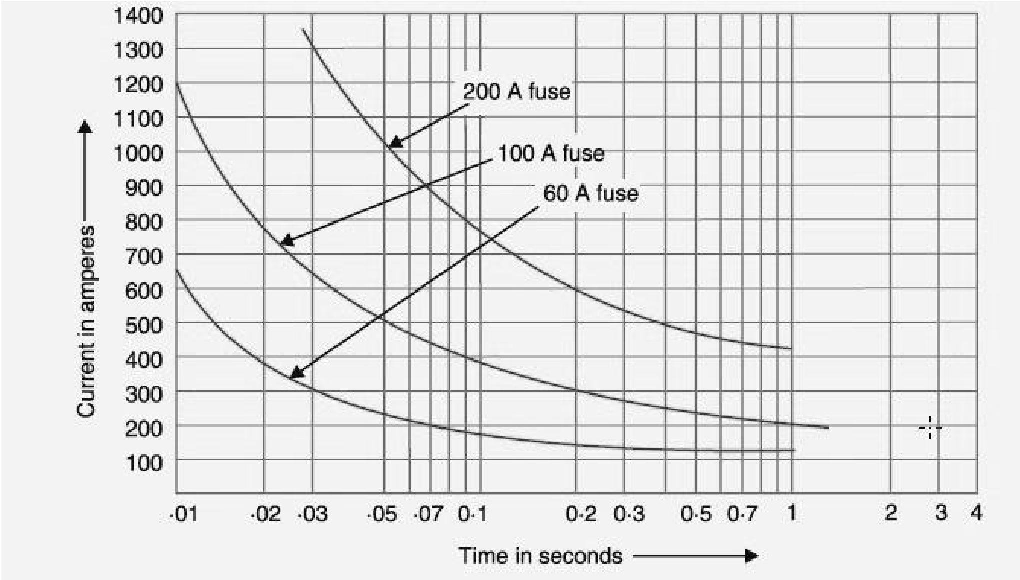


Figure 2.5: Fuse characteristics curve [8]

2.3.4 Instrument Transformers

Voltage transformers & current transformers are known as instrument transformers. The accuracy of protection system completely based on the data provided by CT and VT because all the breaker operations are based on the data and signal provided by the measuring instruments connected with the protection network. Both devices are the basic equipment's used in every protection scheme. The instrument transformers serve two purposes, first it provides known ratio reduced secondary current and voltage levels for the protection and measurement equipment to measure it easily on relays and measuring equipment's. Secondly, it provides a galvanic isolation for the personals from direct contact with the High voltages. There are some other sensors also being developed in the arc protection based on sensing signal of light and pressure.

Voltage Transformers (VT)

The voltage transformer used in the protection system are step-down transformers so that the relays can be able to measure the low voltages and then it is multiplied with the ratio factors to calculate the actual system value. The output voltage depends upon the turn ratios. The basic single-phase diagram of electromagnetic type of transformer is shown in following figure 2.6 shown below,

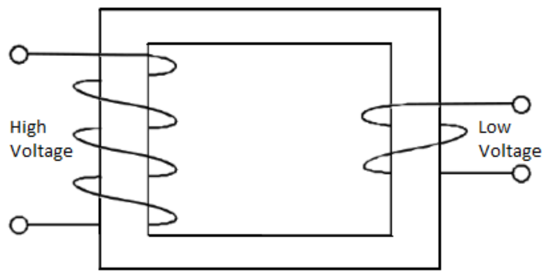


Figure 2.6: single-phase Electromagnetic Voltage Transformer [4]

When the voltages go higher specially on extra high tensions (EHT), the capacitor VT also known as CVT used.

The vector diagram for single phase voltage transformer is shown here with labelled figure 2.7 where, suffix ‘p’ represents primary side parameters and suffix ‘s’ represents secondary side. For 3-phase transformers, the vector diagram will be similar with only phase shifts. The voltage transformers are rated in VA and called VT burden.

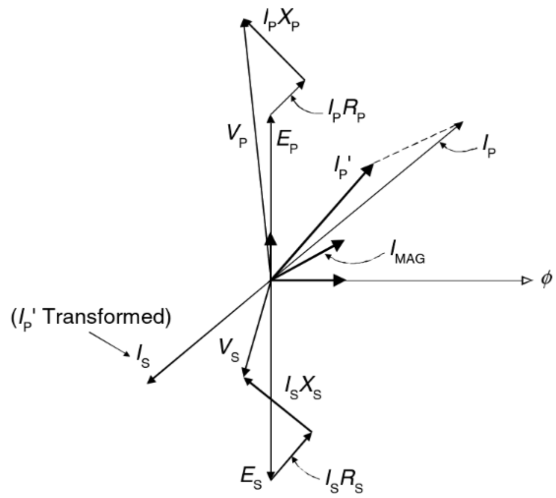


Figure 2.7: single-phase VT Vectors Diagram [4]

VT connections with Relay

The basic diagram for the connection of VT on primary side across the circuit and on secondary side with the relay is shown. This is the most common method of connection to measure 3-phase to neutral and zero sequence voltages (3LN+V0). There are other possibilities also to connect the VT depends upon the type and requirements of the system. L1, L2 and L3 are the 3-phase system. V1_pri, V2_pri and V3_pri are the primary voltages, which flow in the primary side of the voltage transformer. Whereas V1_sec, V2_sec and V3_sec are secondary side voltages and V0_sec is zero sequence secondary voltage which flows in the secondary circuit based on turns ratio and these quantities are measured by the IED where first converted from analog to digital signals and scaled according to the ratings of VT and then displayed on screen.

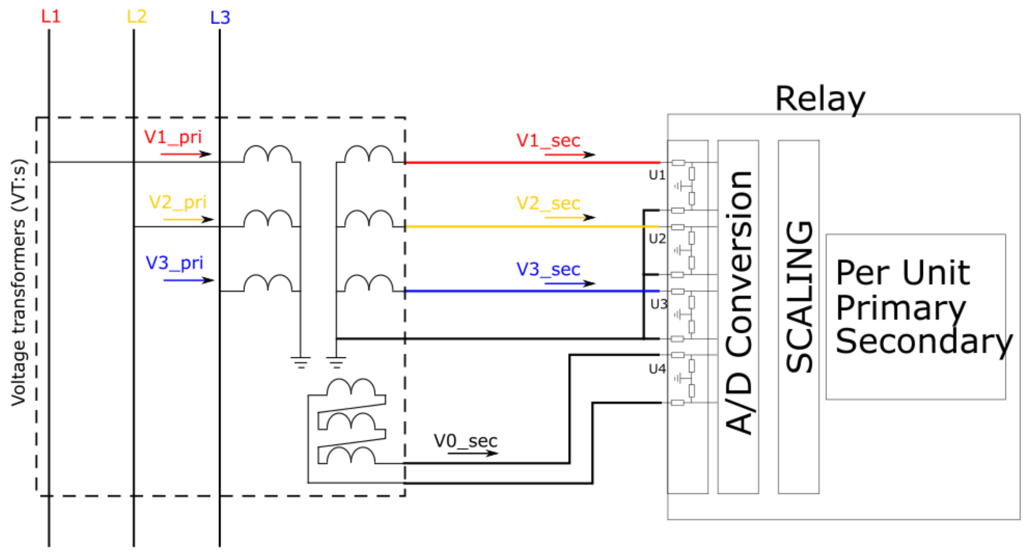


Figure 2.8: VT primary & secondary connection with relay (3LN+V0) [6]

Current Transformers (CT)

The current transformer used in the protection system are step-down transformers so that the relays can be able to measure the low currents and then it is multiplied with the ratio factors to calculate the actual system value. The output currents depend upon the turn ratios. The basic single-phase diagram of current transformer is shown in figure 2.9,

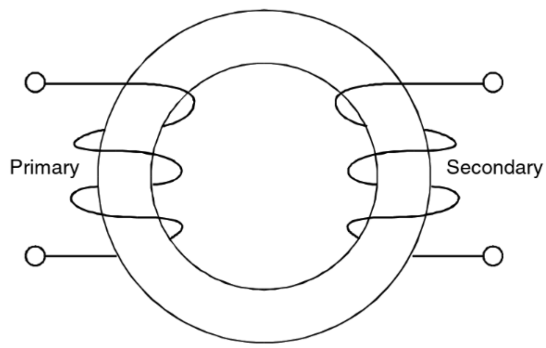


Figure 2.9: single-phase current transformer [5]

The vector diagram for current transformer is shown in figure 2.10. For 3-phase transformers, the vector diagram will be similar with only phase shifts. The current transformers are also rated in VA and called CT burden.

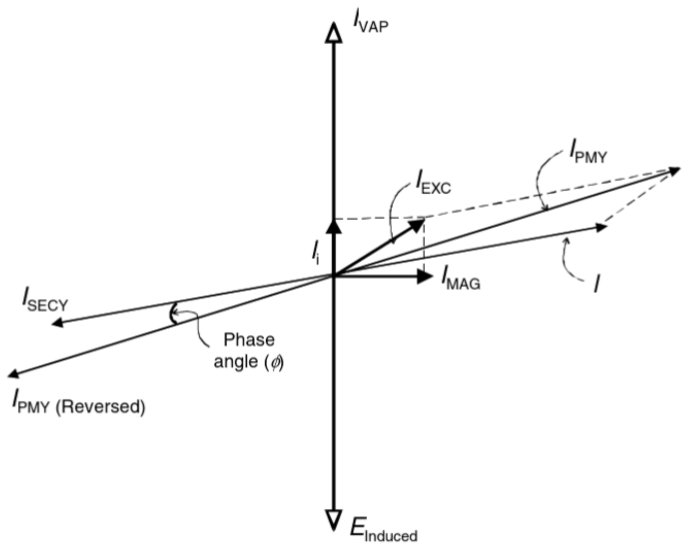


Figure 2.10: single-phase CT Vectors Diagram [4]

The CT saturation curves defines the performance and operation of CT. Since the iron core of CT is non-linear in nature so it farms a B-H curve characteristic which is scattered into 3 regions, Initial, unsaturated and saturated region respectively with knee point as seen in the following CT saturation curve. As seen at the knee point, the curves remain linear, beyond that the curves behave non-linear and for 10% voltage rise on secondary side requires 50% excitation current as observed in figure 2.11 below,

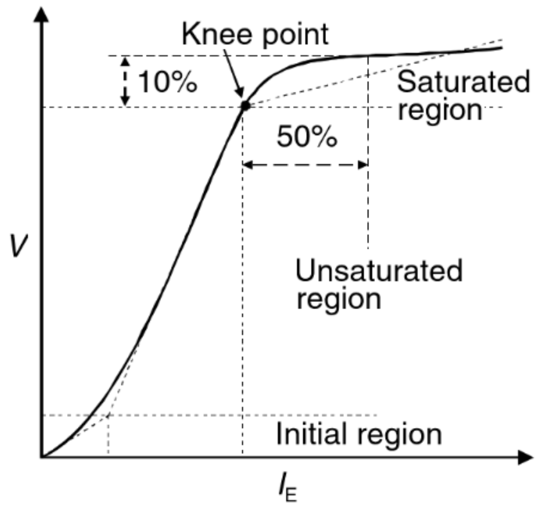


Figure 2.11: CT Saturation Curve [7]

CT connections with Relay

The basic diagram for the connection of CT on primary side along the circuit and on secondary side with the relay is shown. L1, L2 and L3 are the 3-phase system. IL1_pri, IL2_pri and IL3_pri are the primary currents, I0_pri is zero sequence primary current which flow in the primary side of the current transformer. Whereas IL1_sec, IL2_sec and IL3_sec are secondary side currents and I0_sec is zero sequence secondary side current which flows in the secondary circuit based on turns ratio and these quantities are measured by the IED where first converted from analog to digital signals and scaled according to the ratings of CT and then displayed on screen.

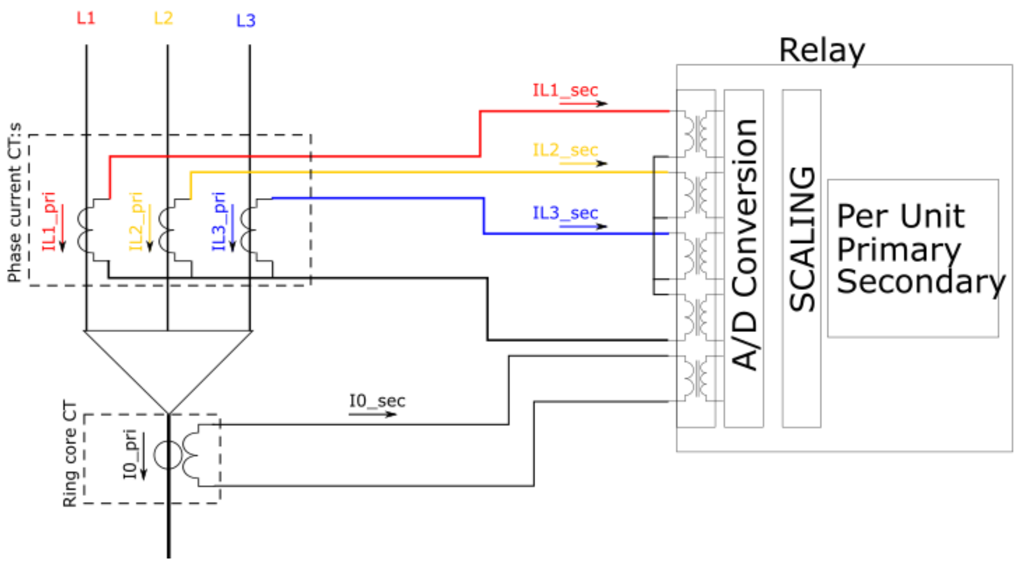


Figure 2.12: CT primary & secondary connection with relays [9]

2.3.5 Auxiliary System

Independent power supply other than the main source required for the relays and breaker to perform operation in the power system, which can be achieved by the auxiliary power supply (DC batteries) as a backup source. DC batteries keeps the relays energized and the DC coils of the circuit breakers to perform operations even the main supply is under a severe faulty condition. Whole protection mechanism depends upon the battery backup system. How good, efficient or reliable protection system is being used, with the failure of battery storage it may of no use. Therefore, it is very important to monitor the batteries condition, storages capacity, charging system, complete supervision and good care is needed in this regard [4].

3. MODELLING METHODOLOGY

This chapter includes the complete methodology of the development of the laboratory model design in software. At first, it describes the main line diagram of the laboratory which includes the number of electrical equipment, as the major network comprise of induction motor and synchronous generator which is modelled using PSCAD software. The protection design of the laboratory is discussed in later chapters.

The modelling methodology starts with the modelling of induction motor and analysing system behaviour and different parameters such as starting current, voltage, speed, electrical and mechanical torques. There are two methods used in the modelling of speed control design of induction motor. Synchronous generator is modelled with the transformer included in the same model. All the important parameters such as terminal voltages, currents, speed and torque is analysed. There is a controller designed for the load frequency control of the generator. A separate simulation model designed for paralleling of synchronous generator and speed-droop characteristics. Finally, a complete model is designed by combining all the network equipment to develop the full laboratory design.

In order to carry out the model designing work, it is important to decide the task and design layout of the laboratory environment before modelling. So, came up with an idea of having a general model which includes every possible equipment of power system as shown in the figure 3.1,

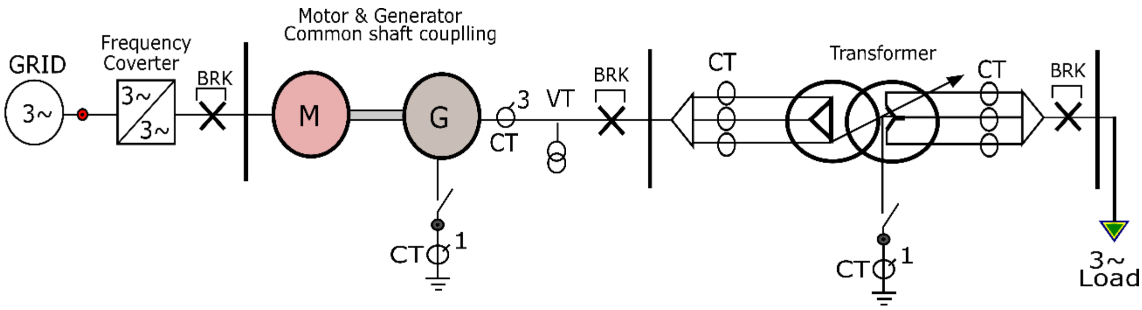


Figure 3.1: Laboratory model layout

The model consists of following equipment,

- Induction Motor
- Synchronous Generator
- Grid source from utility

- Frequency converter
- Transformer (Delta-Star)
- Loads (R-L-C)

The induction motor and synchronous generator are connected on a common shaft, induction motor behaves as a prime mover of the synchronous generator. The generator will have the same speed as the motor due to common shaft coupling, so the frequency of the motor will be controlled by the converter to control the frequency of the synchronous generator.

Before modelling the above laboratory design, the whole modelling process is made in small tasks to produce every equipment individually and at the end all tasks are combined to make the final main model.

The initial tasks are given below,

- Modelling of induction motor
- Speed control design of induction motor
- Synchronous generator modelling with transformer
- Load frequency control of synchronous generator
- Parallel operation of synchronous generators with speed-droop characteristics
- Induction motor & synchronous generator common shaft coupling (Laboratory model)

3.1 Modelling of Induction Motor

Following figure 3.2 shows the model of induction motor, power supplied from the grid source, a step-down transformer is used according to the motor rated voltage and a breaker to control the motor switching. Load torque is selected as the 80% of square of the speed.

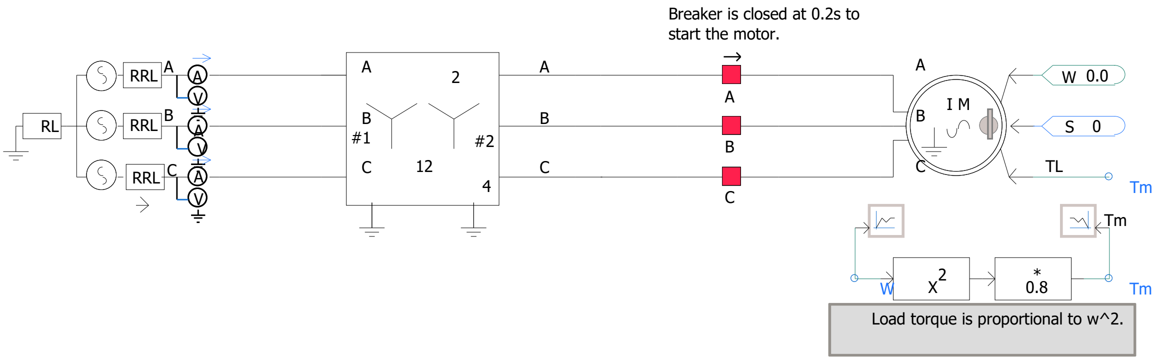


Figure 3.2: Induction motor starting model

As, can be seen in the induction motor inputs, the input 'S' is used to select mode of the operation as speed (1) or torque-controlled mode (0). If motors run in speed control mode so an input ‘W’ speed value can be assigned, and it is also possible to connect with variable signal. Here torque (0) input is selected, then the model calculates the motor speed based on the mechanical motion equation. In this model, S=0 (Torque is selected).

The mechanical load characteristics greatly influence the starting response of the motor, so in the model, the load torque is proportional to the square of speed which effectively an 80% load with respect to the machine MVA rating.

When the simulation is started, the breaker is set to close at 0.2 seconds, the results can be seen in following figure 3.3, only single phase is shown for simplicity.

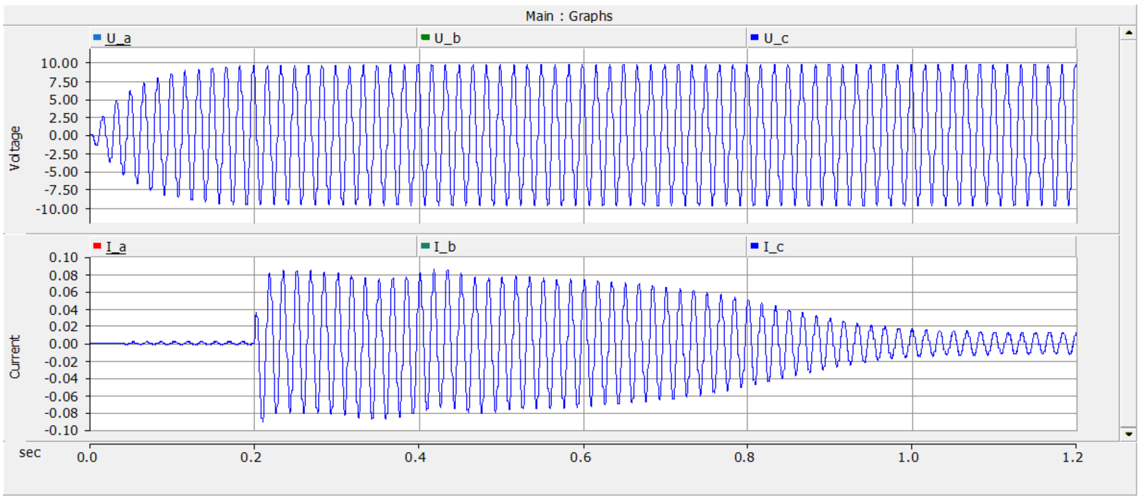


Figure 3.3: Induction motor voltage & current curves

At the instant of 0.2 seconds as the breaker closes, a large starting current is drawn by the induction motor due to its inductive nature as seen in the curves. As the motor start to rotate at its nominal speed slightly lower than the synchronous speed, the currents recover to it nominal value. In order to have the smooth starting of the induction motor, it is important to install some starting methods to limit high starting current. For stronger systems the starting current does not affect much but with weak systems the starting current is so high that cause huge system voltage drops and may affects the whole power system or leads to the disturbance. For laboratory motor, the motor-starter controller will be needed for smooth starting as it is connected with the generator as a load all the time but since here only modelling is done so the effects are not much visible.

Following figure 3.4 shows the variation of reactive power Qr, speed W and the variation of electrical and mechanical torque. All the quantities are represented in per units (pu).

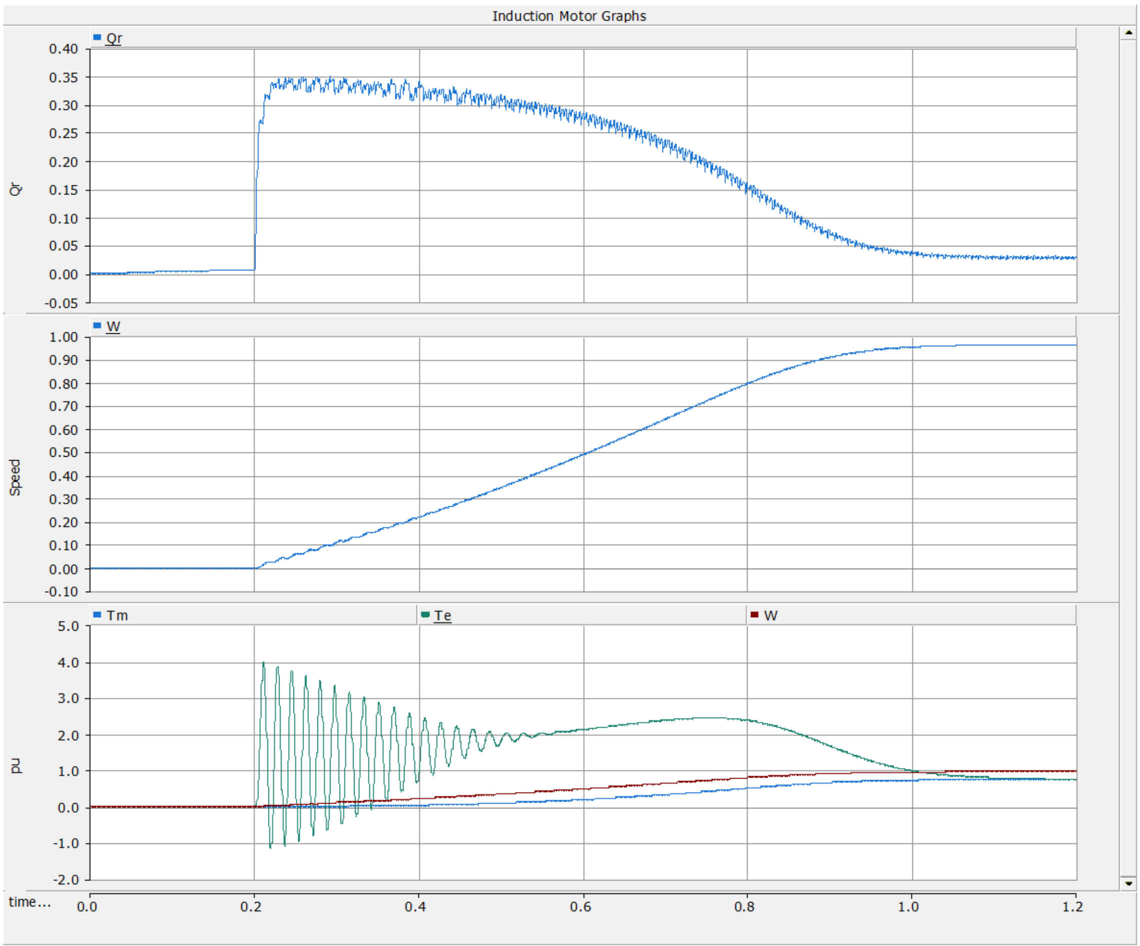


Figure 3.4: reactive power, speed, mechanical & electrical torque curves

3.2 Design of induction motor speed control

There are different methods of speed control of the induction motor, some of them are used here to show the speed control.

(a) Speed control method using variable resistor on Rotor windings

To control the speed of the induction motor, the rotor windings are provided with the external resistor through slip rights to control the speed. This method is only possible in wound round induction motors. The resistance values can be changed to limit the rotor currents and it controls the motor speed.

When the resistors value is zero, the motor runs at full rated speed. Since the motor is induction type, so the motor runs slightly lower than 1 pu.

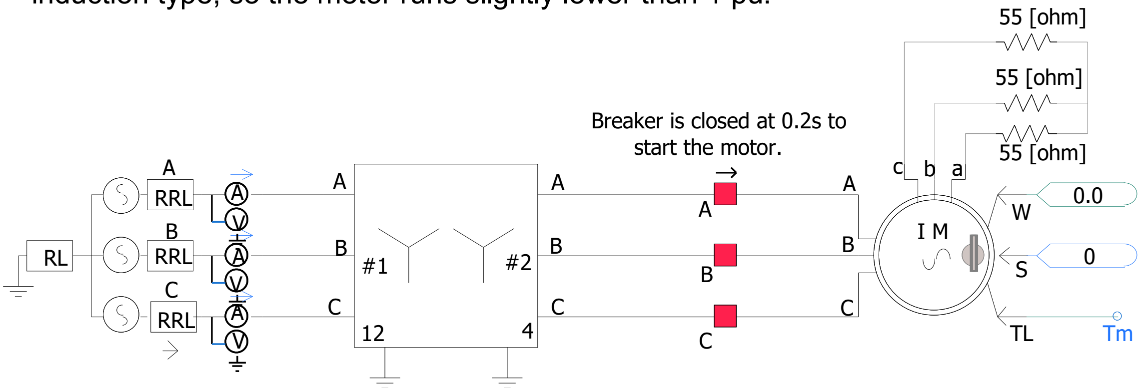


Figure 3.5: Induction motor speed control with rotor resistance

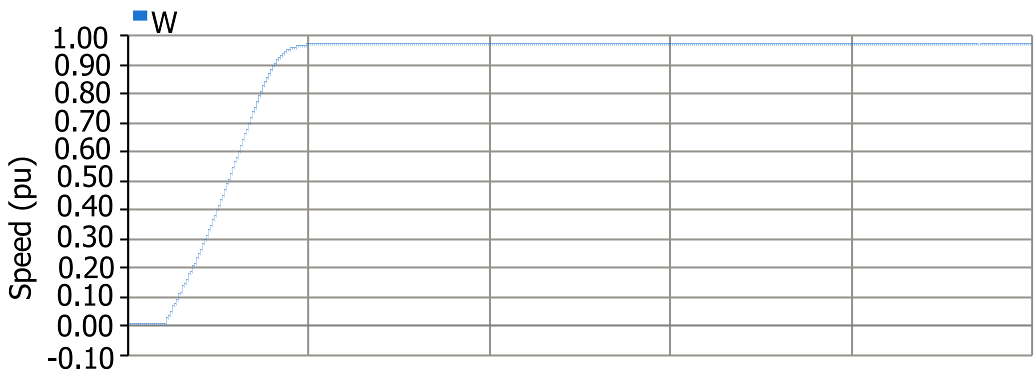


Figure 3.6: Induction motor speed curve with zero rotor resistance

If the resistance values are raised, the speed fall. When resistors are kept on 55 ohms, the speed falls 30% and its 0.7 pu as seen in below figure.

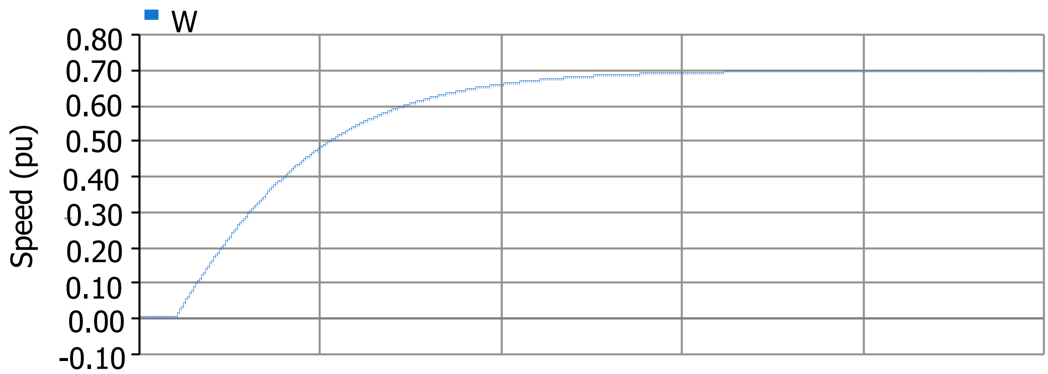


Figure 3.7: Induction motor speed curve with 55 ohms rotor resistance

When resistors are kept on 100 ohms, the speed falls 40% and its 0.6 pu as seen in below figure.

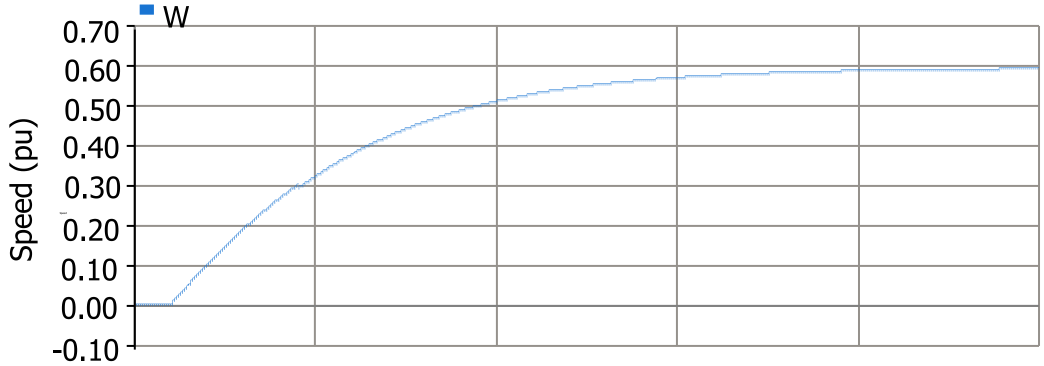


Figure 3.8: Induction motor speed curve with 100 ohms rotor resistance

It is possible to use higher value of resistance to reduce more speed and get higher torques. This speed control method is easy to use but it is avoided due to lower efficiency and extra loss of energy in the rotor windings and on lower speeds the efficiency is badly affected. This method is used in application where higher torques are required such as in cranes and where the efficiency is not the main concern.

(b)Speed control method using frequency converters

To control the speed of the induction motor, the most common method used are the frequency converters. In the modelling, variable frequency control is used on the source. By varying the frequency, motor speed is controlled. The model can be seen in the figure below

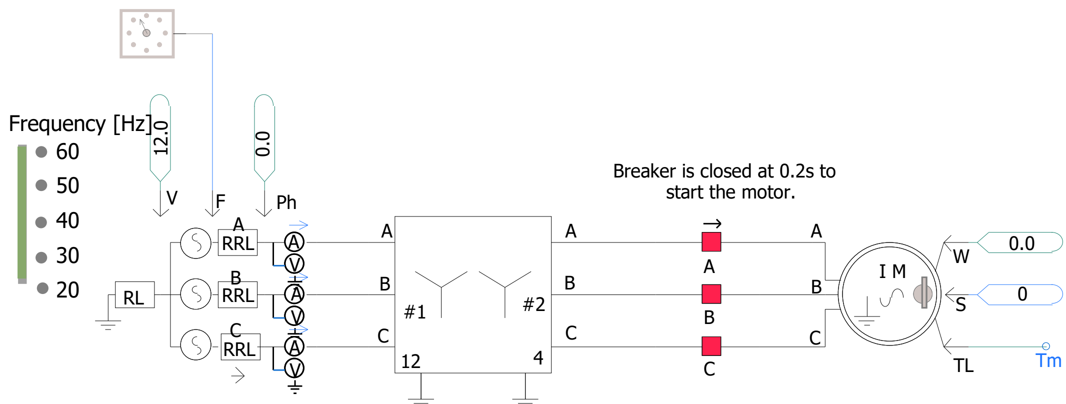


Figure 3.9: Induction motor speed control using converters

Following graphs shows the speed curves on different range of frequencies.

When f=60Hz, the motor rotates at full nominal speed, since the motor is induction type, so speed is slightly lower than 1 pu.

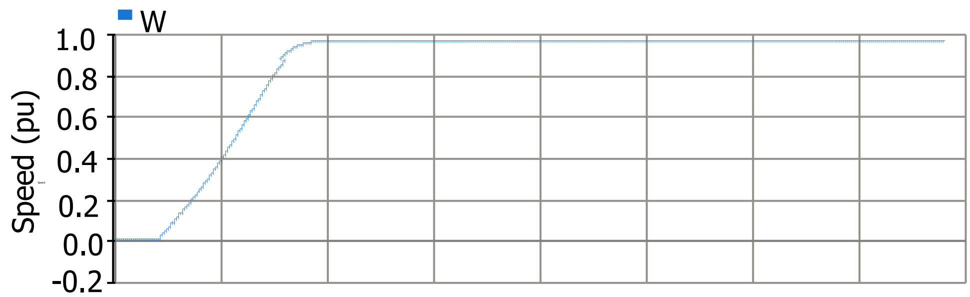


Figure 3.10: Speed curve at 60Hz converter setting

When f=50Hz,

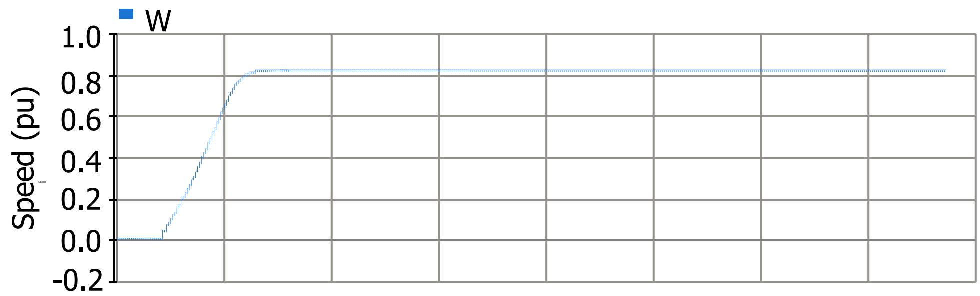


Figure 3.11: Speed curve at 50Hz converter setting

When f=40Hz,

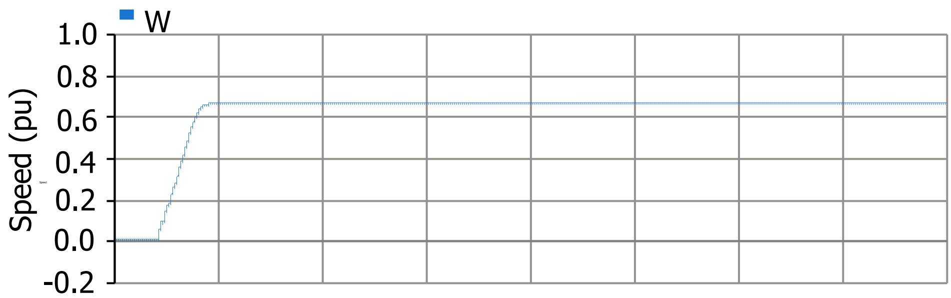


Figure 3.12: Speed curve at 40Hz converter setting

The converters are most reliable equipment to control the speed. It is also important to protect the converters from high starting motor currents and it produces harmonics in the system, so filters are also needed.

3.3 Synchronous generator modelling

The following model is designed to show the normal operation of the synchronous generator. Its various parameters such as voltages, currents and speed when it starts. The model is connected to the transformer and a load with the breaker as seen in following diagram.

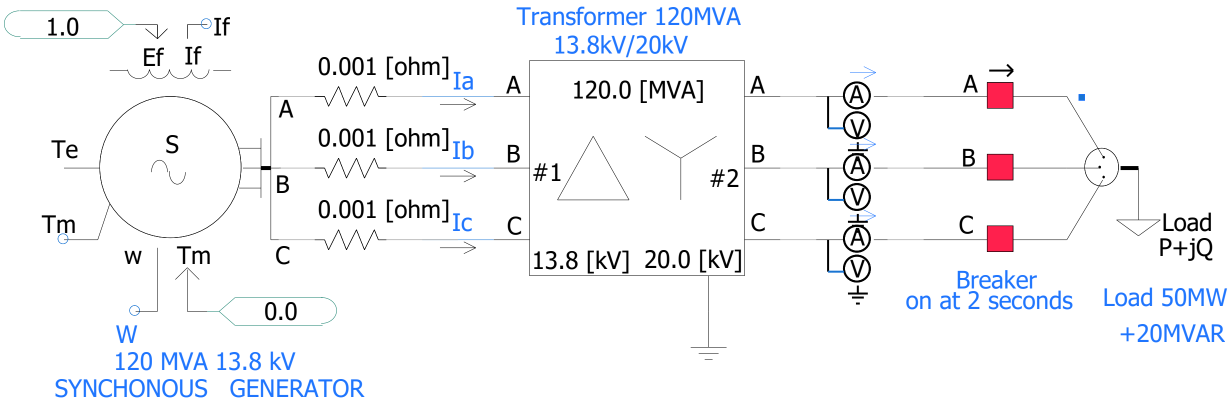


Figure 3.13: Synchronous generator model

There is an option to control field excitation by selecting Ef values of the generator. Tm inputs provide the load torque selection.

There are two curves of currents shows in following figure 3.14, the first one is the system line currents, initially there is zero current flowing in the circuits, now when connected the load breaker at 2 seconds, the current starts to flow and it raises higher and then stabilize to the normal value. At the same time the current goes high and voltage dips. Similarly, field current is 1pu on normal condition and raises its value when load is connected and produces similar high spikes.

Raising load to higher values cause the terminal voltages to drop. The curves are shown here,

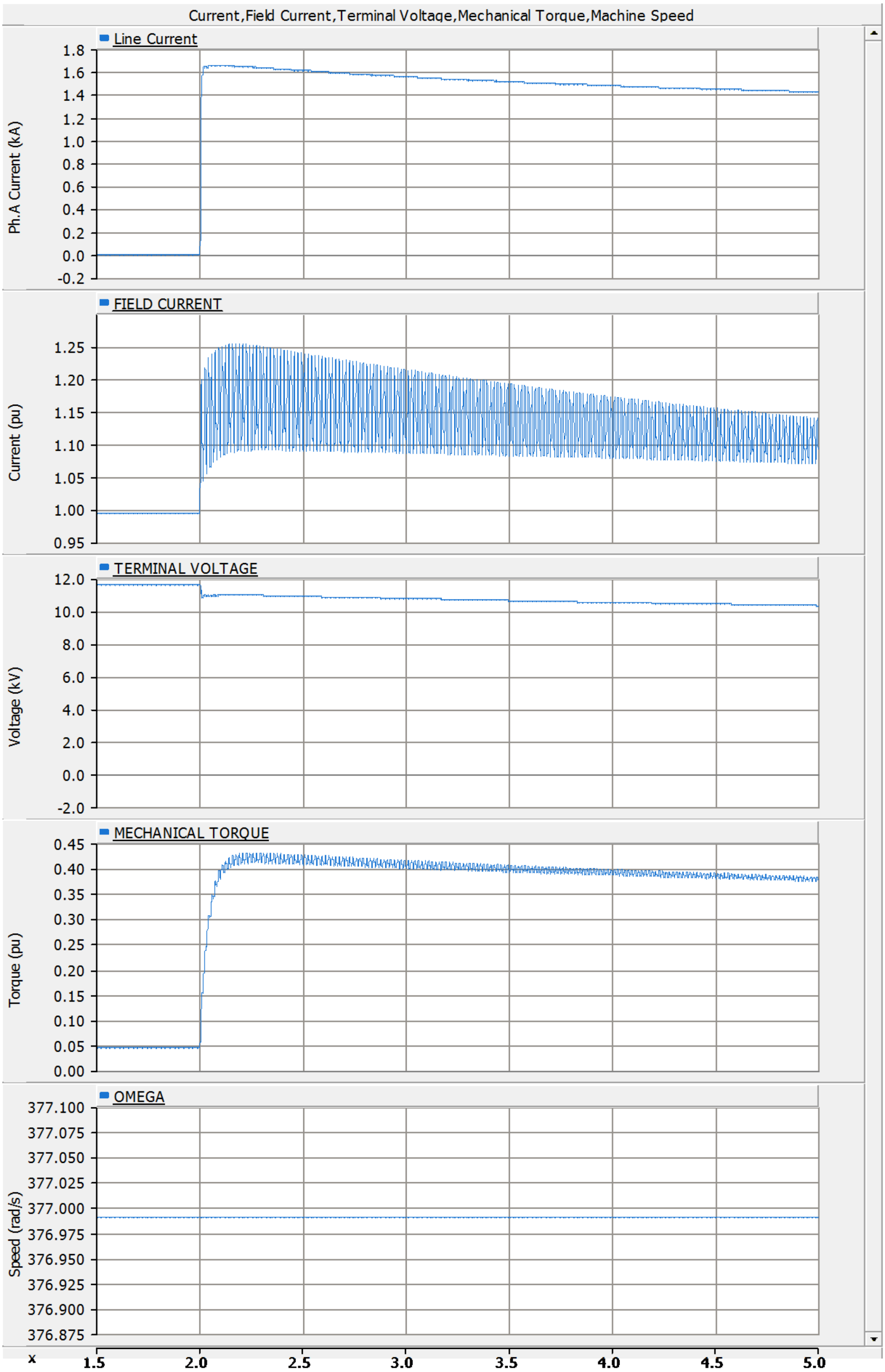


Figure 3.14: Synchronous generator parameters curve

3.4 Load frequency control of synchronous generator

The system frequency changes when heavy loads are connected or disconnected from the power system and if this is not done in a controlled manner, it can lead the generator out of synchronism. To keep the generator running on a nominal frequency with no major change with the load variation, a controller is designed.

When there is one fixed load connected to it all the time, while the other load is connected or disconnected suddenly by desired operation or on a fault. Since the sudden variation in the heavy loads create a disturbance for the power system and leads the generator to go out of synchronism. In order to protect the system, it need to have a load frequency controller that senses the frequency and raise or lower it to compensate the load variations. The controller is shown in following figure 3.15 below,

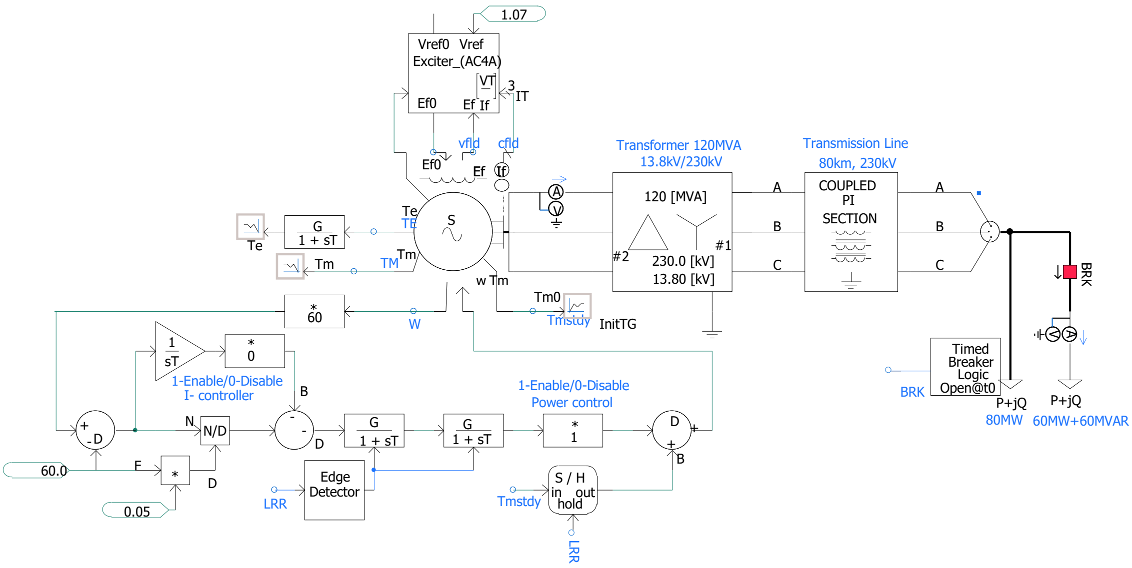


Figure 3.15: Load frequency control of synchronous generator

The following curves shows different parameters of the system, such as system voltage, current, power generated, load curves, electrical and mechanical torque of the generator.

Curves start with the nominal values when the constant load is connected, at 2 seconds time when another heavy load connects, generator increases the power generation to supply for extra loads. Voltages drops as current increases and torque values also go high as seen in following figure 3.16.

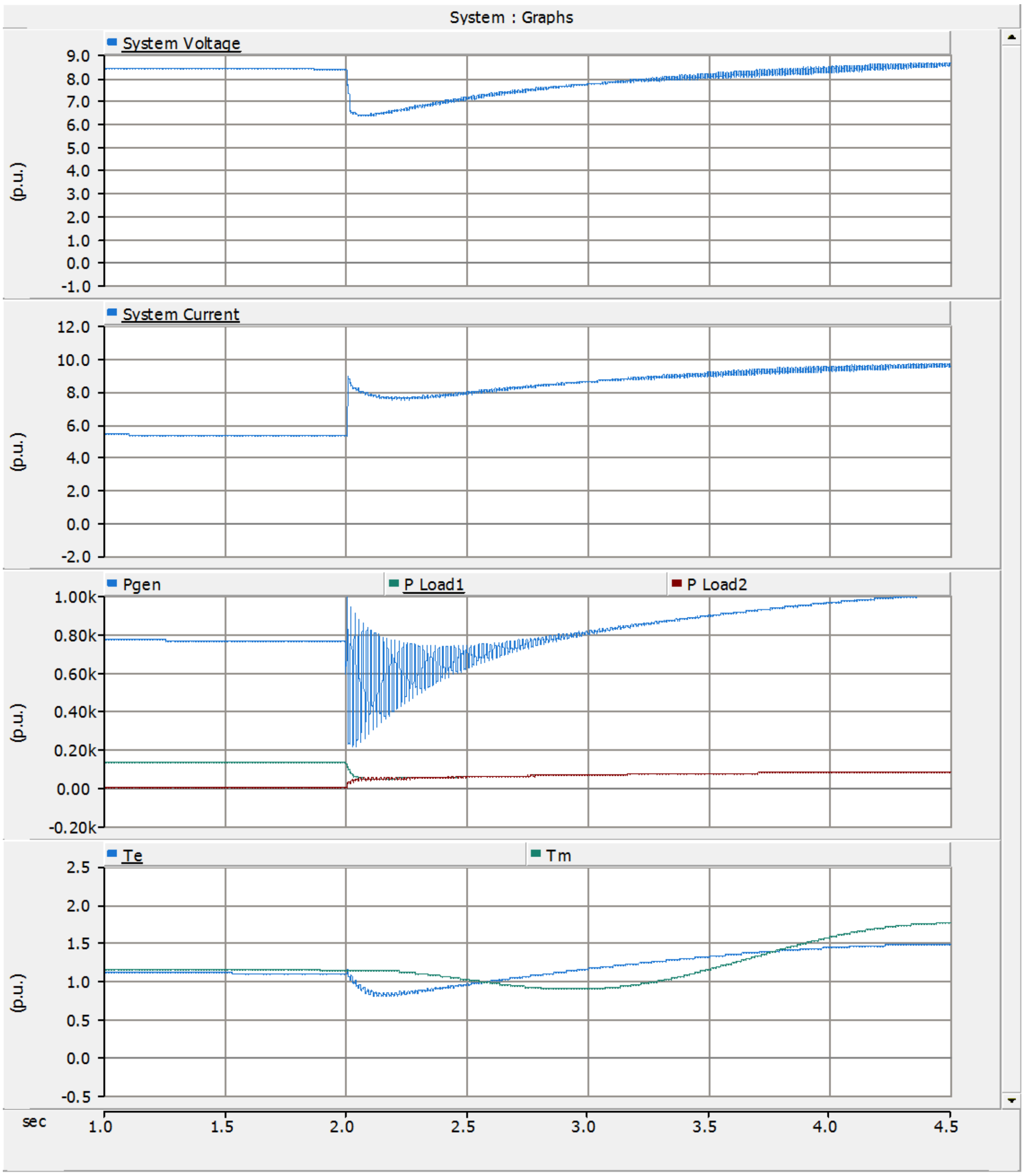


Figure 3.16: Load frequency control of model curves

The controller circuit can be seen here, it receives the generator frequency all the time and compares it with the nominal frequency (60Hz) and tries to keep it in the nominal range.

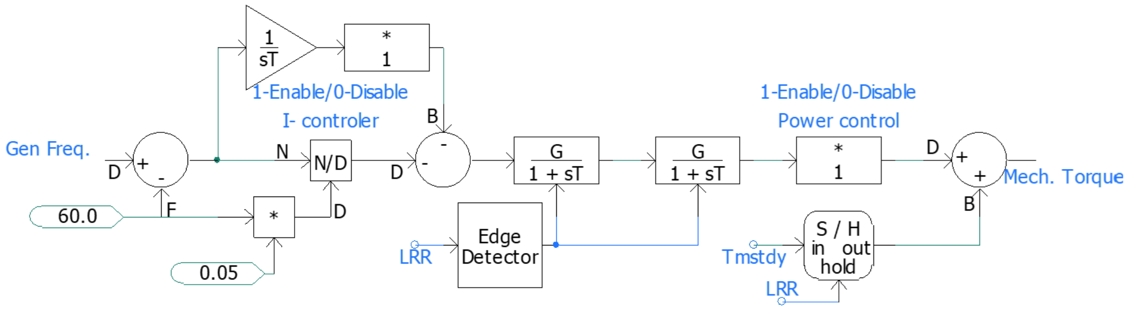


Figure 3.17: Controller load frequency control

The primary control is faster, it stabilizes the system, but speed-droop causes steady-state frequency deviation even if power balance is achieved by the control actions. Secondary control is needed to return frequency back to nominal value.

When the controllers are disabled, the heavy lead is connected at 2 seconds of operation time, as you can see the speed curve, it starts to drop the frequency and if it is not controlled further, it leads the generator to go out of synchronism.

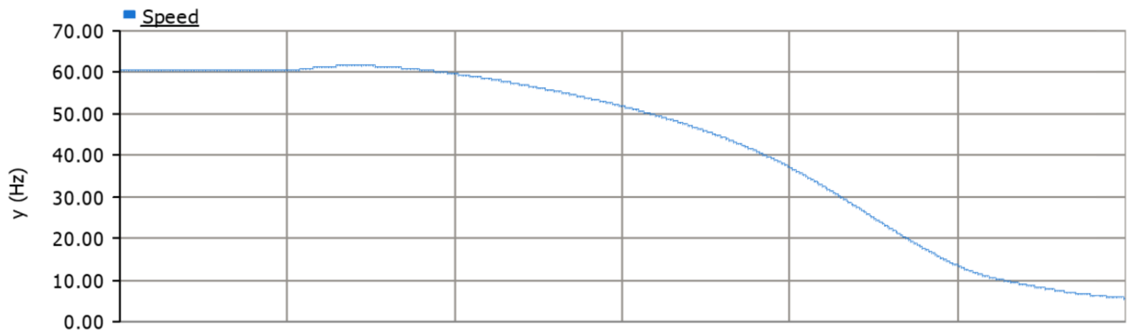


Figure 3.18: Load connection without controller

Similarly, when the heavy lead is connected at start and removed at 2 seconds of operation time, as you can see the speed curve, it starts to raise the frequency and if it is not controlled further, it leads the generator to go out of synchronism.

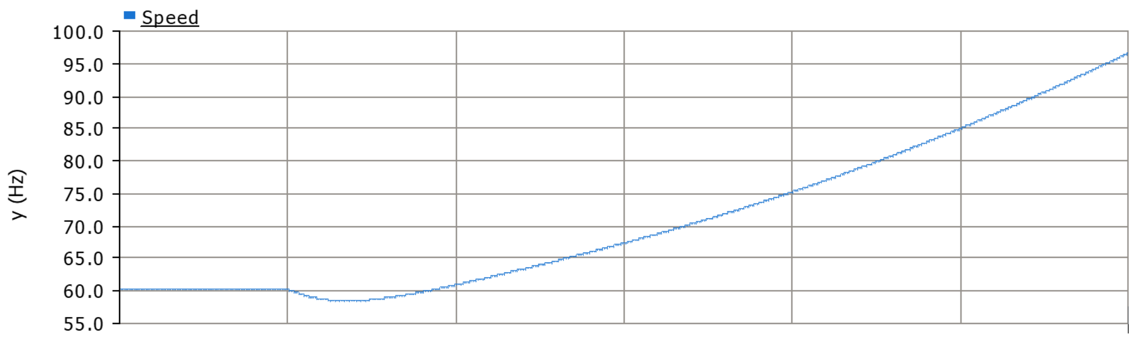


Figure 3.19: Load disconnection without controller

To overcome this problem, we have placed a controller, that senses the load and the frequency of the system and tries to maintain it to the nominal value of 60Hz.

When the power controller is in active mode, it tries to maintain the frequency of the system, so as the load connects, the controller starts to maintain the error, but it brings it to 59.2Hz and stabilize it. It keeps the system running on the current frequency with a small error as seen in following curve,

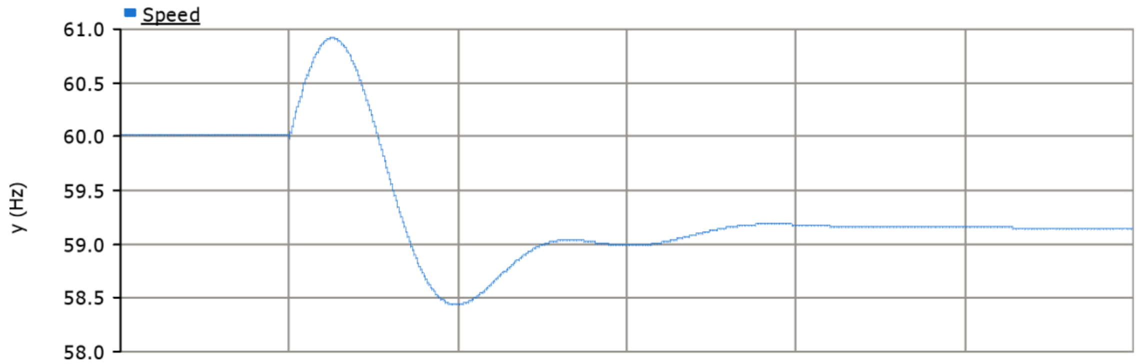


Figure 3.20: Speed curve when P-controller is active

Now, to compensate the error an integral controller is introduced in the system to overcome the error. Both controllers together bring the system back to normal in 10 seconds as seen in the following curve.

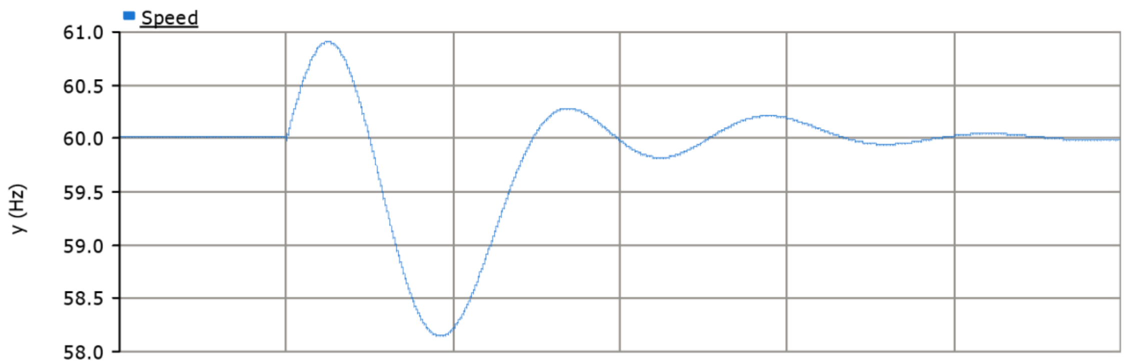


Figure 3.21: Speed curve when PI-controller is active

3.5 Synchronous generator paralleling with Speed-droop characteristics (R)

The speed-droop characteristics decides the load sharing when multiple generators are made to run in parallel. With the help of this characteristics it is possible to set the load sharing from each parallel generator. Normally, it is desired to get the power from all generator equally based on ratings, but in some cases when the generator uses different kind of energy sources and it is desired to get more power from the generator which produces cheap power. For example, the power producing companies want to produce more power from windmills and solar system as the cheaper and cleaner energy source.

To demonstrate the load sharing of multiple generators running in parallel can be seen from the following simulation model with P-controller is shown in figure 3.22 below,

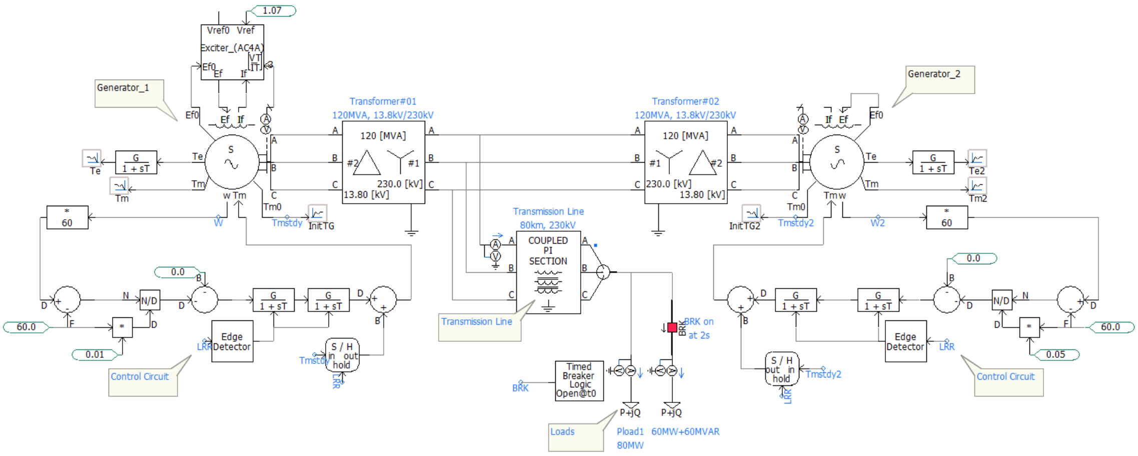


Figure 3.22: Synchronous generator paralleling with Speed droop-characteristics (R)

In the following model, the generator #01 kept on R=0.01 and for generator #02 R=0.05, which shows that with having same power rating generator #01 will share more load as compare to generator #02 as seen the graph show below.

For sharing more load, more power production is needed, so here generator #01 produces more power and more electrical and mechanical torque.

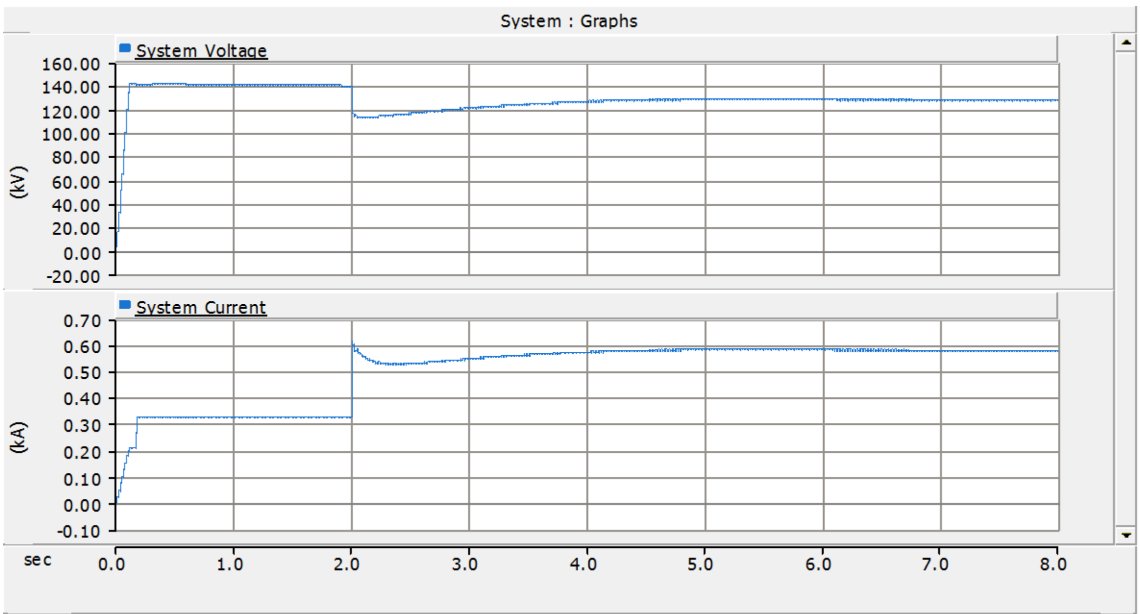


Figure 3.23: Voltage and current curves of synchronous generator

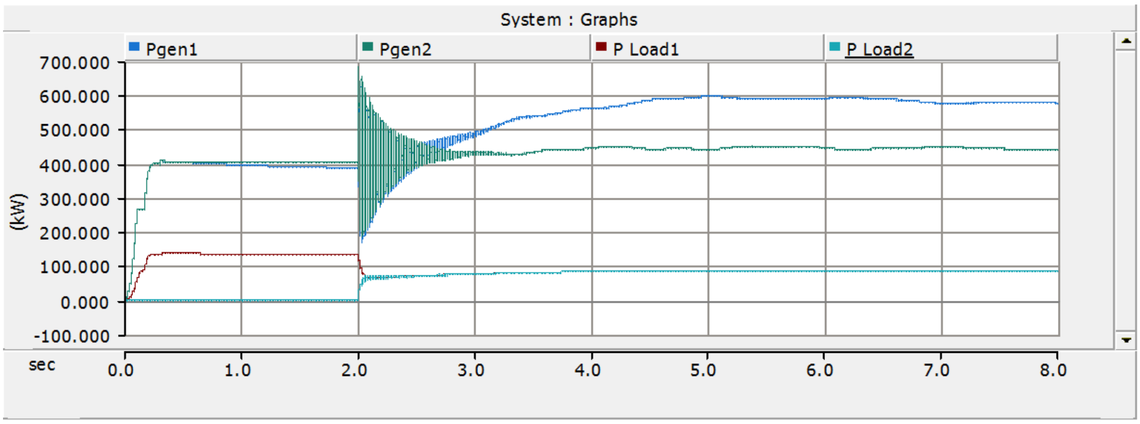


Figure 3.24: Power generation and load curves of synchronous generator

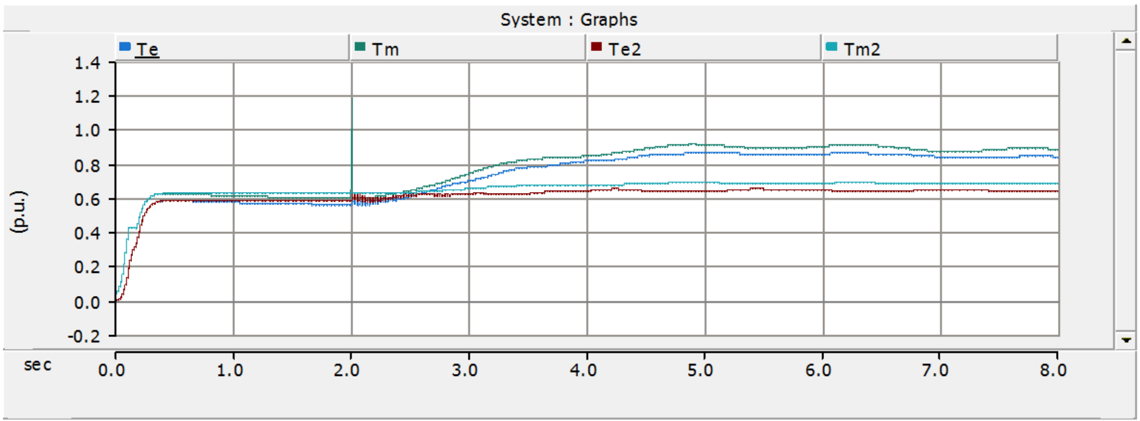


Figure 3.25: gen-1 and gen-2, electrical & mechanical torques

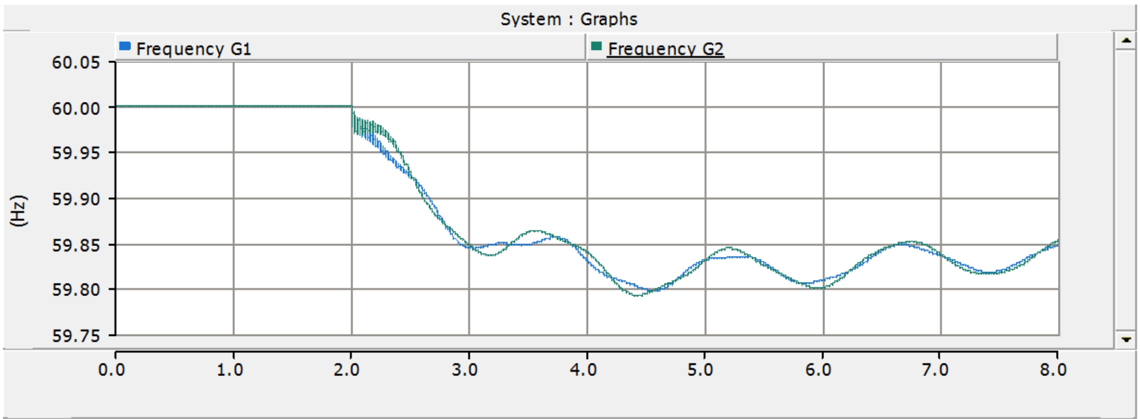


Figure 3.26: Gen-1 and Gen-2, frequency curves

Here, only P-controller is activated, so there is a steady state error in frequency. PI controller can be used to remove the error and brings the frequency back to 60Hz.

3.6 Designing of LABORATORY setup model

After completing the task, we have each of the model component independently modelled to perform some test individually. Here the combining of all small models together to make the main model as shown in following figure, the motor and generator are placed on common shaft.

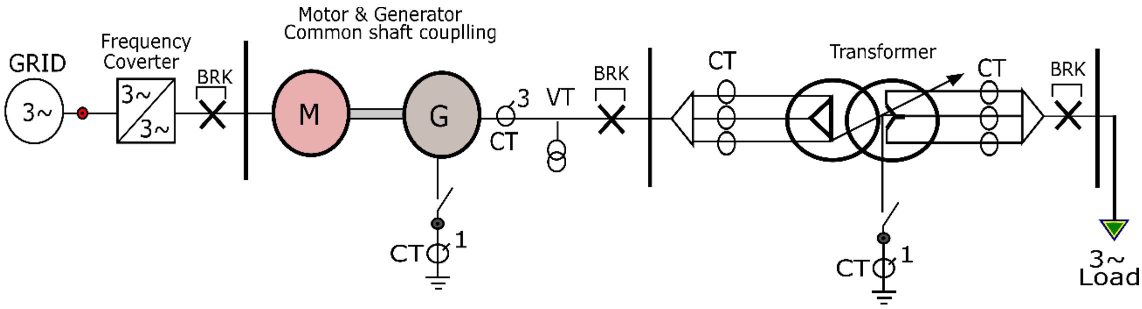


Figure 3.27: Laboratory model graphical layout

The above given line diagram is modelled using PSCAD software and similar system is developed as shown below in figure 3.28,

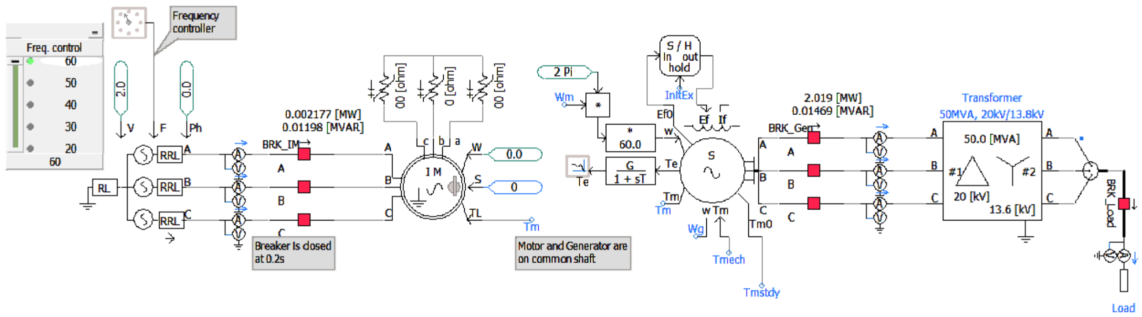


Figure 3.28: Laboratory model PSCAD design

Following are the motor and generator frequency meters, where it is possible to visually monitor the speed/frequency changes done in the motor side and its effects on the generator side.

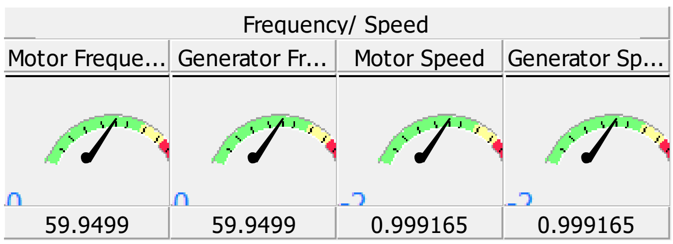


Figure 3.29: Laboratory model motor & generator speed/frequency curves

It's also possible to see the current and voltage phasor of the system, residual fault current (I0) and voltage (U0) phasor during the time of the fault.

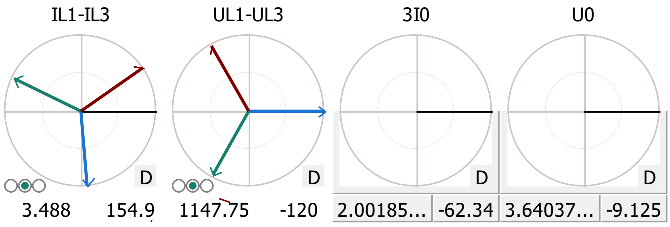


Figure 3.30: Generator current, voltage, 3I0 and U0 phasors

Following meters gives the system impedance in real time, so it's possible to check the system impedance before, after and during the time of fault.

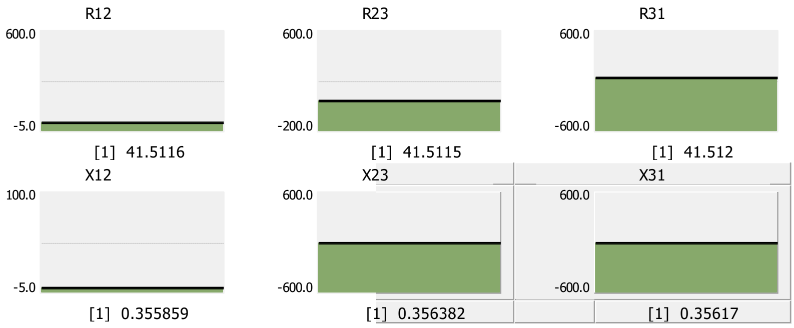


Figure 3.31: Generator side system impedances

The system impedance and phasors are produced by using Fast Fourier Transform (FFT).

4. APPLIED FAULTS AND SYSTEM BEHAVIOUR

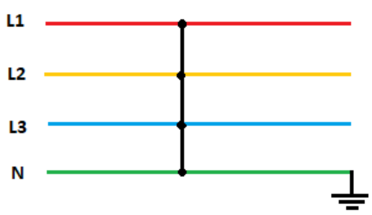
The faults are natural and inevitable, but it is possible to take corrective actions on time to control the system and safe it from any damage, which can only be achieved by good design of protection system, schemes and protection equipment. In order to apply the protection system, it's crucial to study the faults, types of faults and system behaviour on various conditions. The fault can be a bolted with zero impedance ideally or it can be with impedance depend upon the fault location from the source. The fault currents completely depend upon the type of fault with impedance, so less the impedance higher the currents. On the network if you move away from the generator, the system impedances increase and the fault current will be lower and when the fault is towards the generator, the lower the impedances and higher will be fault current. The fault current close to the generating stations especially on the generator terminals are considered as most sever faults with very high magnitude of current. The faults are divides into symmetrical and unsymmetrical types which are discussed in detail.

4.1 Symmetrical and Unsymmetrical faults

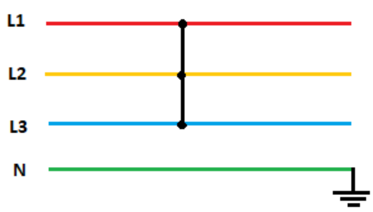
a. Symmetrical faults

Symmetrical faults are always 3-phase fault and can happen in the following conditions, when

- 3-phases are short-circuited to each other
- 3-phases are short-circuited & also connected to ground



(a) L-L-L-G fault



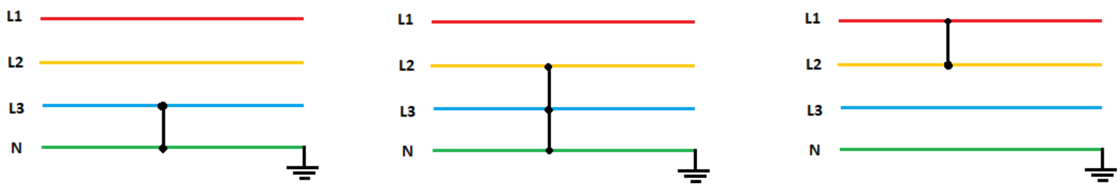
(b) L-L-L fault

The above-mentioned faults are balanced, hence only positive sequence network is needed to analyse these faults. The behaviour of the synchronous generator and transmission line of the power system at the time of symmetrical short-circuit can be studied by modelling these power system components into a Resistance-Inductance (R-L) series circuit [10] and 3 phase system can be analysed easily by converting it to single phase.

b. Unsymmetrical faults:

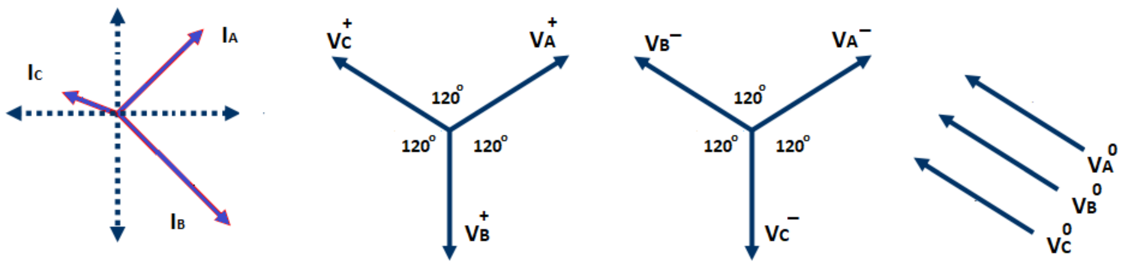
Unsymmetrical faults do not involve the three phases faults.
Types of unsymmetrical faults are:

- Single line-to-ground (L-G) fault
- Double line-to-ground (L-L-G) fault
- Line to line (L-L) fault



(a) L-G Fault (b) L-L-G fault (c) L-L fault

This type of fault causes the system unbalanced, with unbalanced currents and phase shifts. Such systems are complex to solve but Dr. D. L. Fortescue proposed a method convert unsymmetrical system to symmetrical systems, the desired results are obtained first and then systems are converted back to unsymmetrical. Three vectors (voltages and currents), regardless of how unbalanced they are, can be replaced by three sets of balanced vectors. These balanced vectors are the positive-sequence, negative-sequence and zero-sequence system of vectors which can be further described as, (a) unbalanced vectors (b) positive phase sequence components (c) negative phase sequence components and (d) zero phase sequence components. the positive sequence component phasors are of equal magnitude, spaced 120 degrees apart and move in the same direction sequence as the phasors of the unbalanced system, and may be represented in complex forms [10].



(a) Unbalance vector (b) positive sequence (c) negative sequence (d) zero sequence

4.2 Faults on Synchronous Generator

Synchronous generator short circuit test:

The following model is designed to show the faults on the synchronous generator connected in the network and graphs to show the different parameters at condition of faults. Here the generator connected with the step-up transformer and a load is connected. The fault is placed near the load.

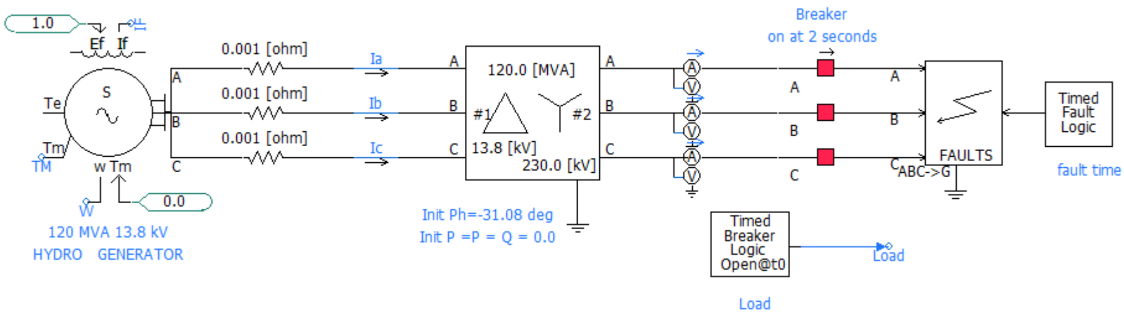


Figure 4.1: Synchronous generator short circuit test model

3 Lines to ground fault (L-L-L-G)

For performing the short circuit test, a 3 phase - ground fault is placed at the time of 2s for about 50ms and results are obtained to check the currents, voltages & torque of the generator.

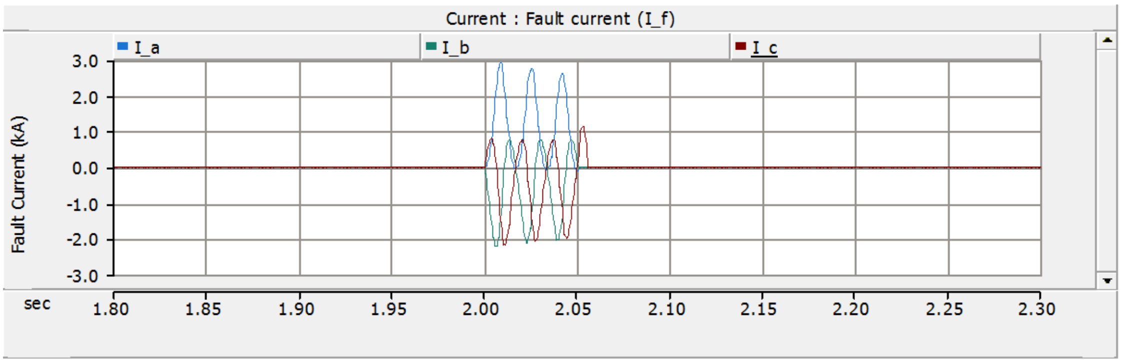


Figure 4.2: Synchronous generator currents on (L-L-L-G) fault

The above curve shows the fault currents, initially there is no fault, so no fault current seen. At the time of 2s there is a fault for about 50ms, the current overshoots as seen in the curve. After 50ms when the fault is removed at 2.05s the fault current disappears.

Similarly, field current is 1pu on normal condition and raises its value on load and similar high spike on fault as seen in following curve,

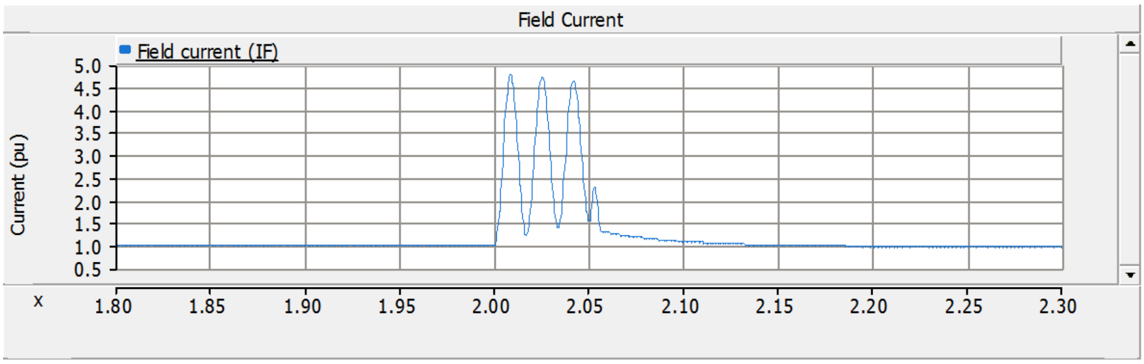


Figure 4.3: Synchronous generator field current

Following curve shows the system voltage, at the time of fault it falls to almost zero but as the fault disappears it goes back to normal.

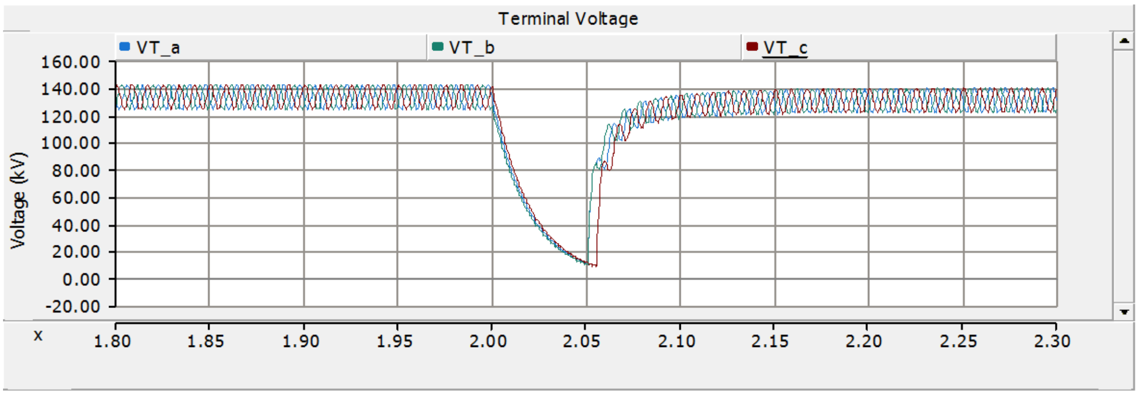


Figure 4.4: Synchronous generator terminal voltages

The mechanical torque also overshoots as seen in following curve,

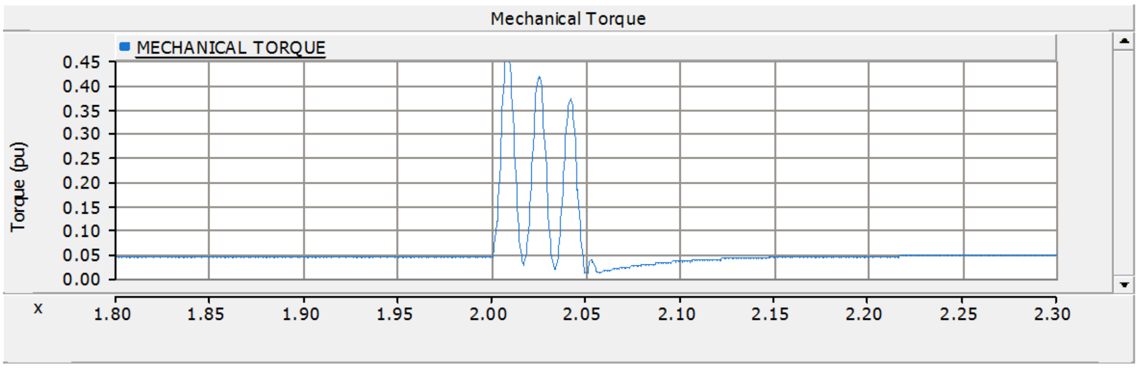


Figure 4.5: Synchronous generator mechanical torque

There is not big change observed on the speed, because fault is for short duration and speed of the synchronous generator depends upon the prime mover.

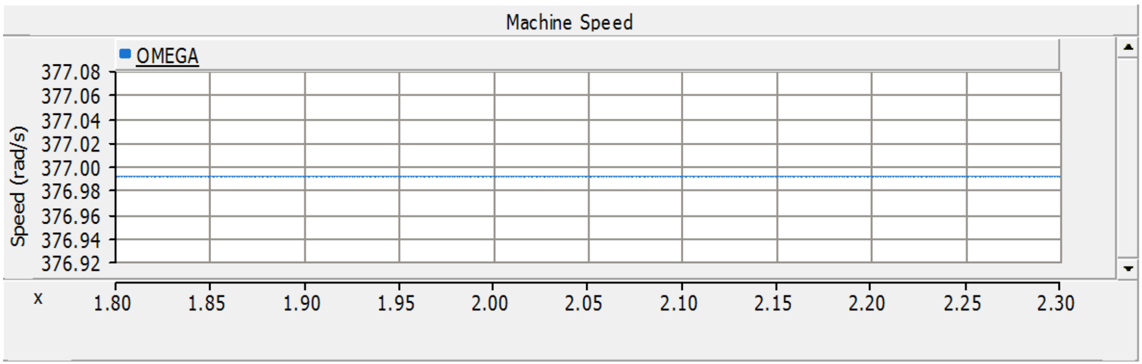


Figure 4.6: Synchronous generator speed (rad/s)

Double Line to ground fault (L-L-G)

When the 2 phases short circuited with the ground at 02s, the curves appear as follow, The fault current start to flow at the time of fault only and appears in only 2 faulty phases,

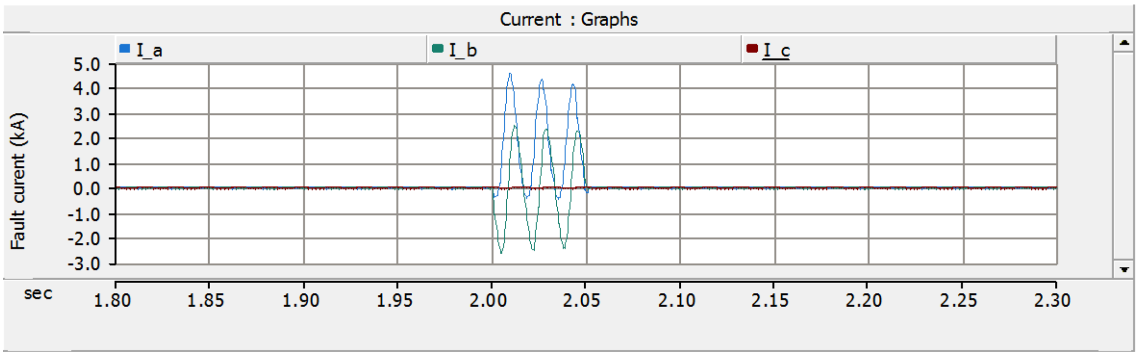


Figure 4.7: Synchronous generator fault currents on (L-L-G) fault

The terminal voltages fall to very low value, but as the fault removed from the system, the voltage moves back to normal values.

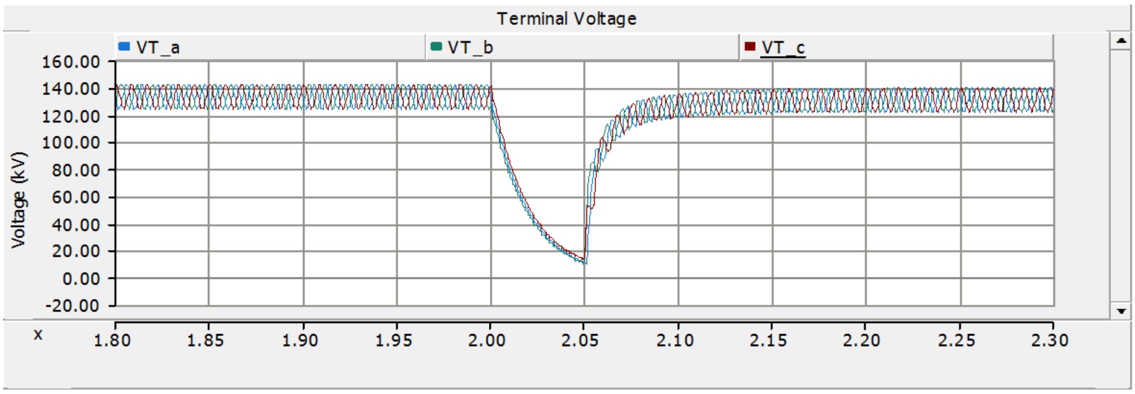


Figure 4.8: Synchronous generator voltages on (L-L-G) fault

Line to ground fault (L-G)

there is single-phase short circuited with the ground, so only one fault current flows,

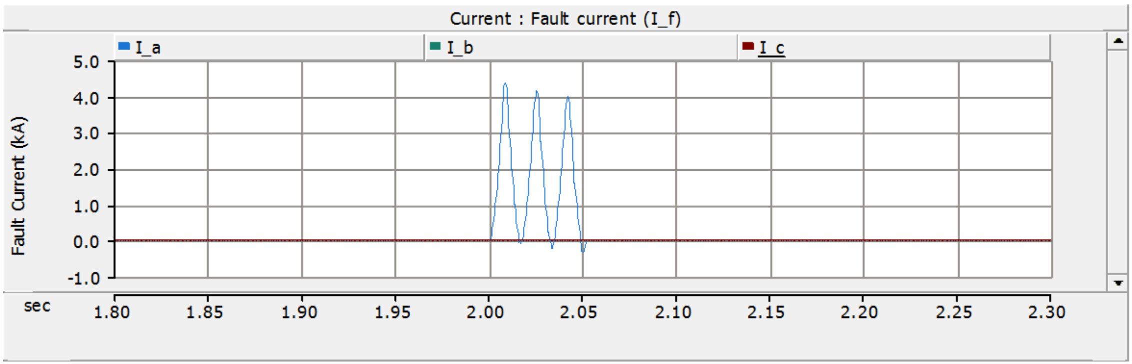


Figure 4.9: Synchronous generator fault currents on (L-G) fault

The voltage of faulty phase drops and the voltage of healthy phases goes 1.73Un higher,

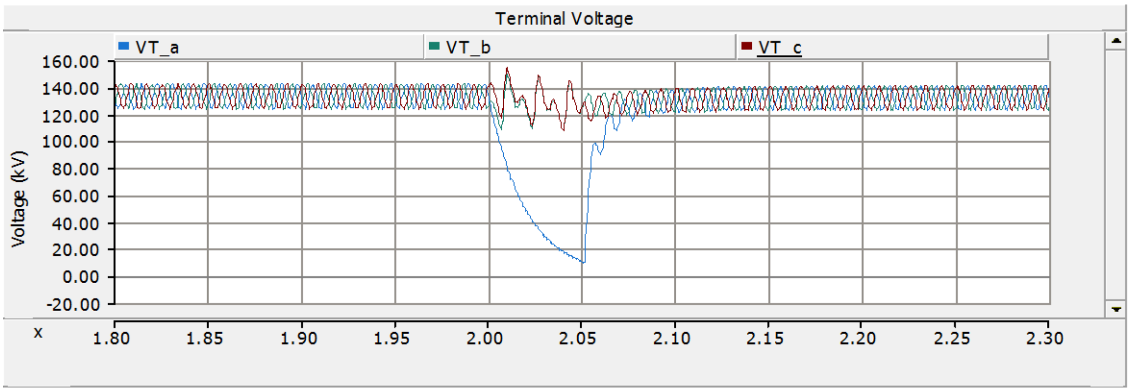


Figure 4.10: Synchronous generator voltages on (L-G) fault

2 Lines short fault (L-L)

There are 2-phases short circuited with each other, the current curves become 180 degree apart, as seen here in the curve,

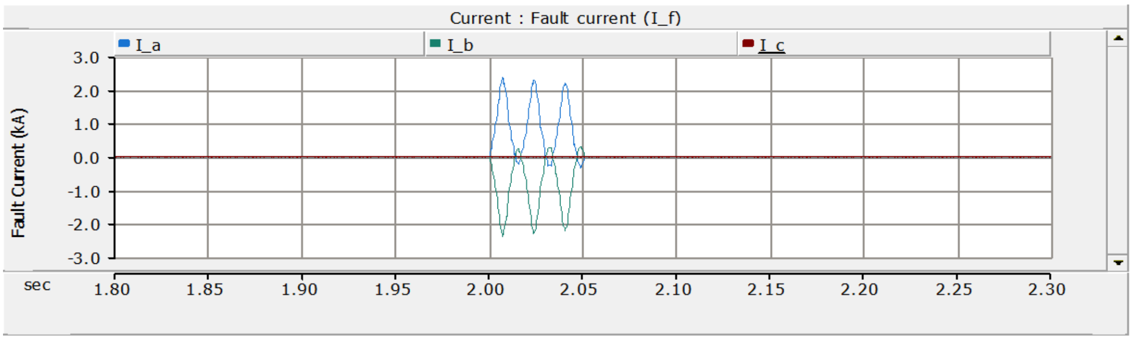


Figure 4.11: Synchronous generator fault currents on (L-L) fault

The voltages of faulty phases drop low and health phase goes higher to 1.73Un times.

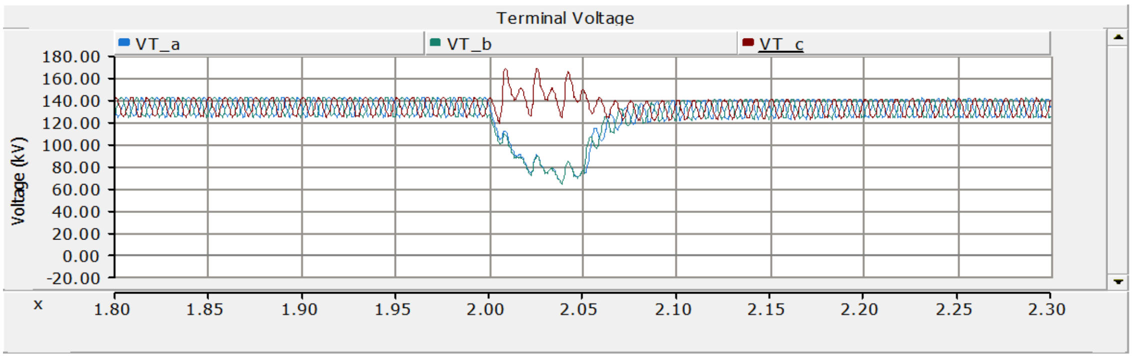


Figure 4.12: Synchronous generator voltages on (L-L) fault

4.3 Faults on Induction motor

The induction motor faults are analysed on following model, where the faults are applied on the motors power supply terminals.

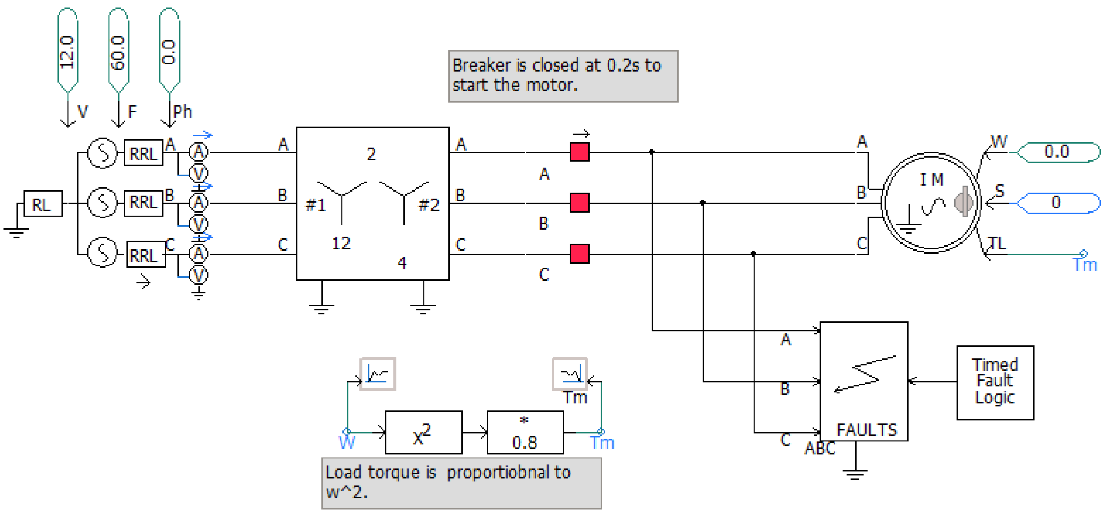


Figure 4.13: Induction motor short circuit test model

The motor runs in torque control mode where load torque is squire of the speed.

3 Lines to ground fault (L-L-L-G)

When 3-phases are short circuited with the ground, the voltages fall and current goes 5 times higher than the nominal values, since when a fault is placed at 1 sec time, the fault current and voltages are shown in following curves,

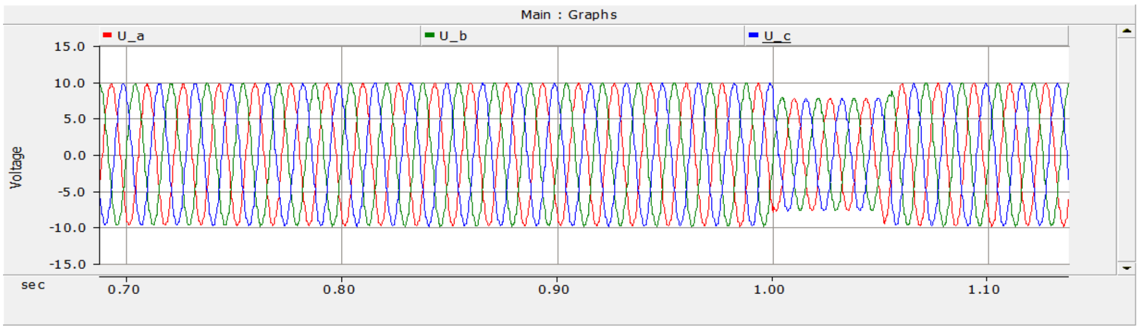


Figure 4.14: Induction motor voltages on (L-L-L-G) fault

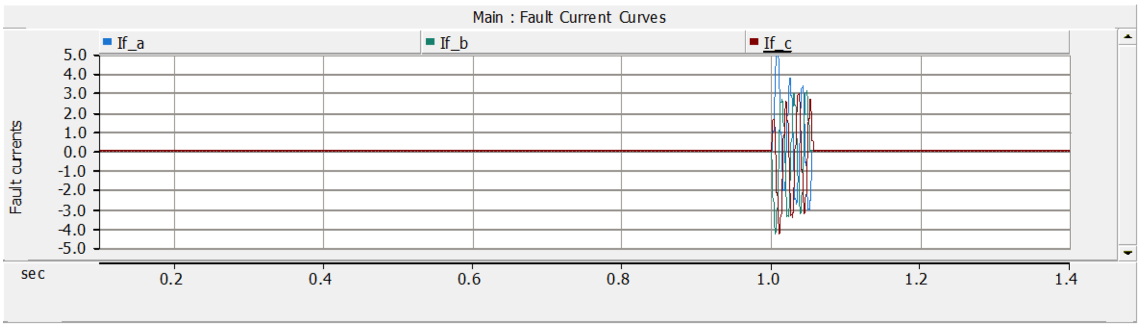


Figure 4.15 Induction motor currents on (L-L-L-G) fault

The line current is zero at start, at 0.2 sec when the breaker is connected to supply the motor, it starts to draw the higher current in start and then normalizes. At 1sec when the fault appears, it draws high current as seen in following curve,

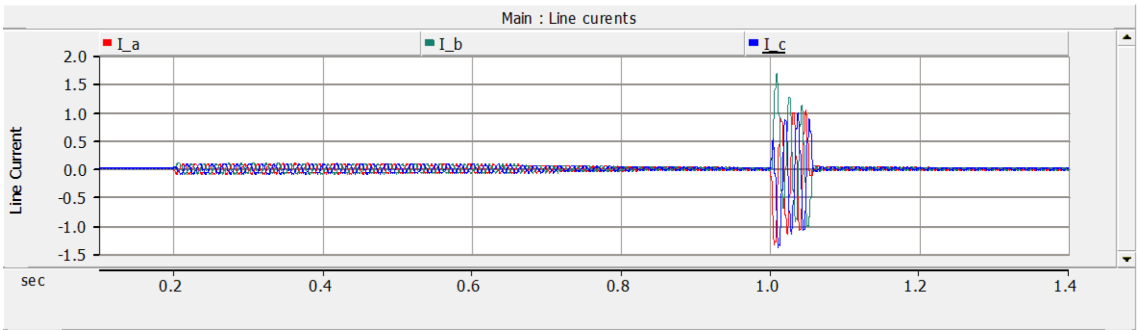


Figure 4.16 Induction motor system currents on (L-L-L-G) fault

The electrical and mechanical torque behaviour is normal, at time of fault electrical torque goes in negative,

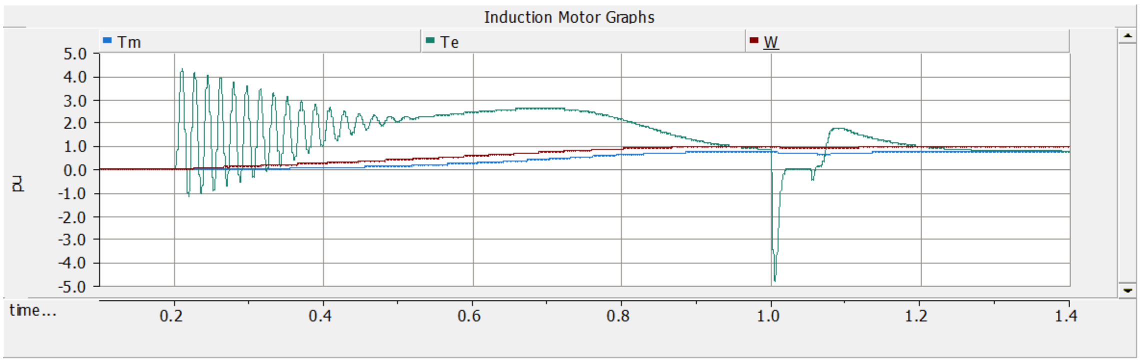


Figure 4.17 Induction motor electrical & mechanical toque with speed

And, there is a short dip in the speed at the time of fault. If fault stays longer, the speed drops to zero.

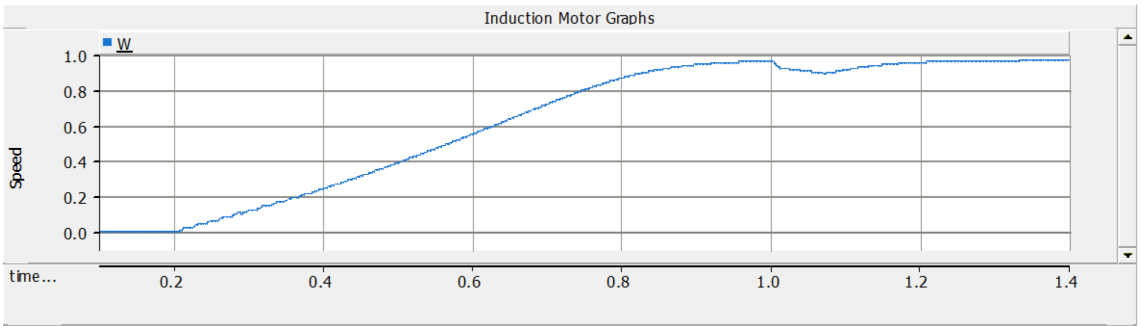


Figure 4.18 Induction motor speed curve

The motor draws high reactive power at the time of fault,

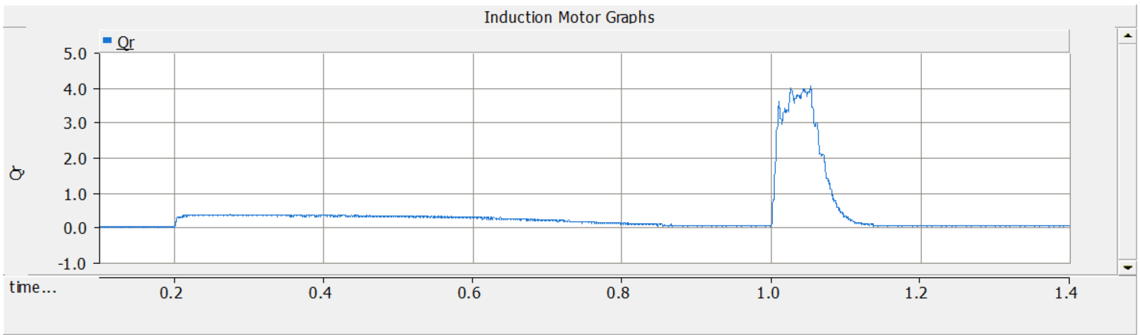


Figure 4.19 Induction motor reactive power curve

Double line to ground fault (L-L-G)

When 2-phases are short with ground, the faulty phase voltages drop,

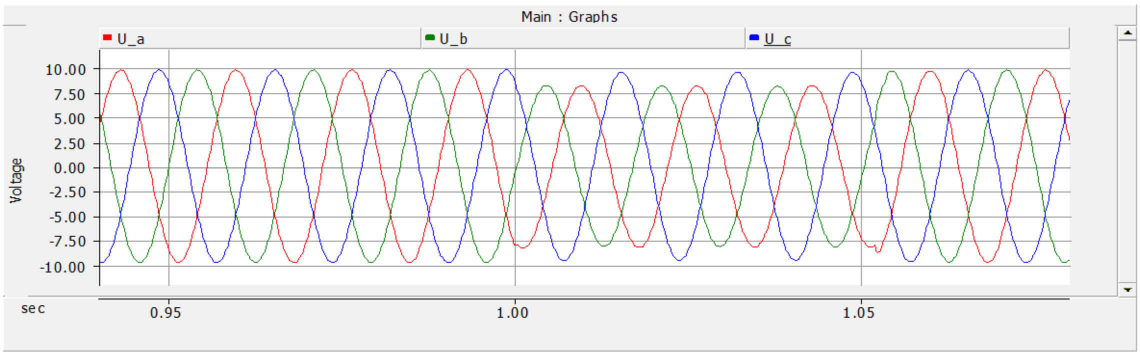


Figure 4.20 Induction motor voltages on (L-L-G) fault

The current also goes higher of the faulty phase and current of healthy phase to 1.73 times the normal value.

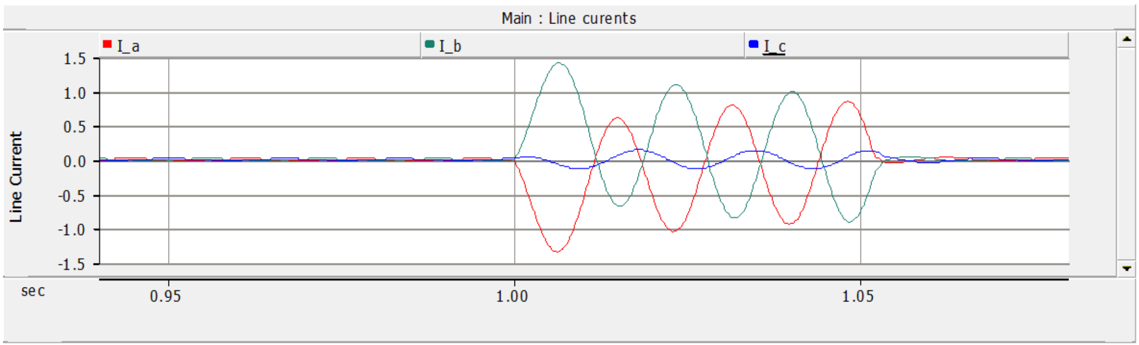


Figure 4.21 Induction motor system currents on (L-L-G) fault

Line to ground fault (L-G)

When single-phase is short circuited with ground, the faulty phase voltages drop,

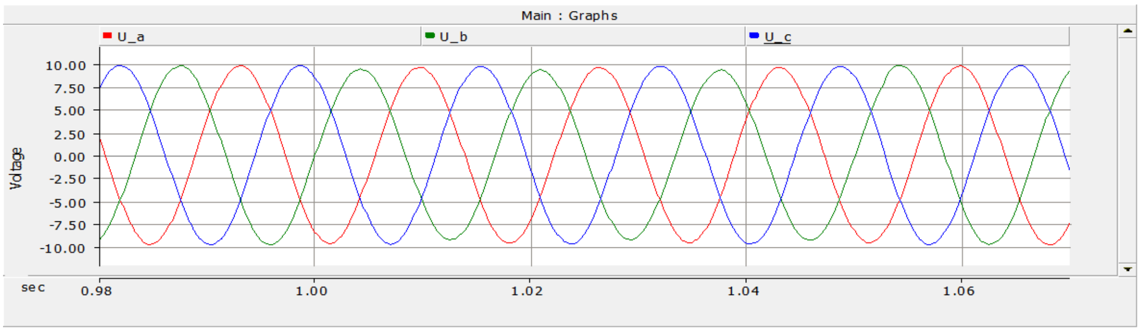


Figure 4.22 Induction motor voltages on (L-G) fault

The current also goes higher of the faulty phase and current of healthy phase to 1.73 times the normal value.

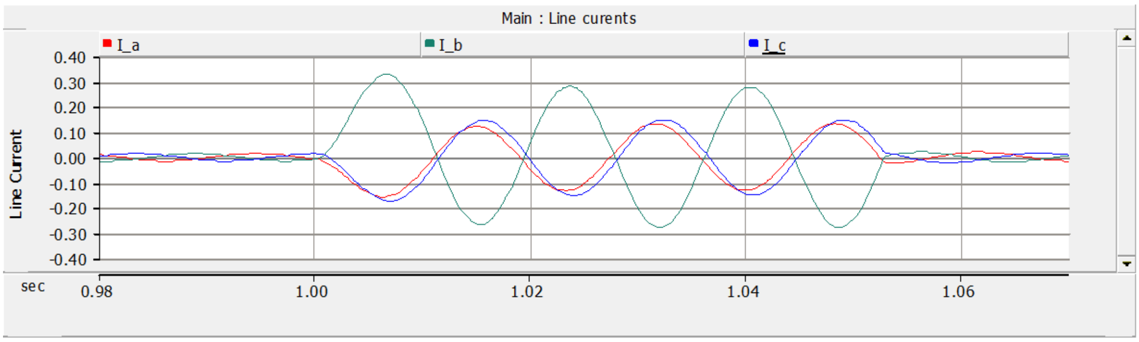


Figure 4.23 Induction motor currents on (L-G) fault

2 Lines short (L-L)

There are 2-phases short with each other, the current curves become 180 degree apart and health phase voltage goes higher as seen here in the curve,

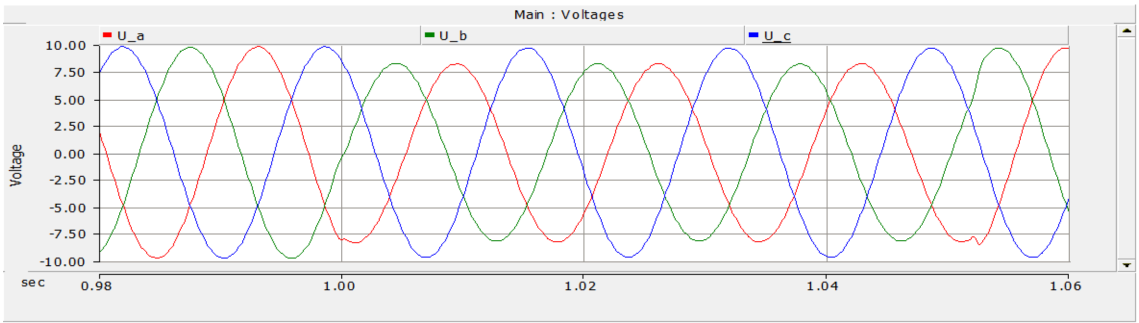


Figure 4.24 Induction motor voltages on (L-L) fault

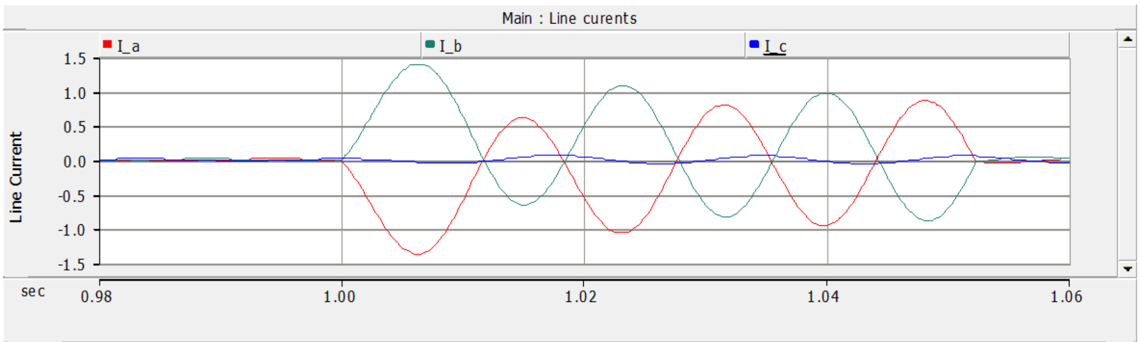


Figure 4.25 Induction motor system currents on (L-L) fault

Low voltage power supply

If supply voltage of the motor drops lower than the nominal value, it affects the speed of the motor. More voltage drop leads the motor to complete stop and draws higher currents which can lead to a damage to the motor.

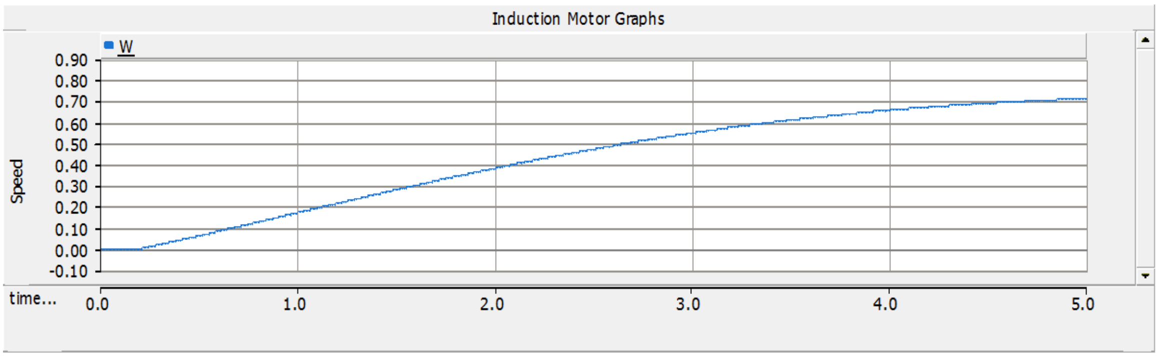


Figure 4.26 Induction motor speed on low voltage power supply

In the above curve, when the motor us supplied with the lower voltage, it reduces the speed as seen in the curve and there will be point where motor completely stops.

5. PROTECTION DESIGN OF THE LABORATORY MODEL

In order to protect the laboratory model, it is important to protect each unit individually with its own protection and a backup support in case of primary protection failure. In this section the individual protection of each equipment is discussed.

5.1 Synchronous generator protection

The generator is the most critical unit at the power plant and all the other supporting units stops if there is any issue with the supply unit, so it is very important to protect it a highest priority. Synchronous generator needs the following protections in system,

- Generator protection in general (Voltages & currents)
- Excitation
- Synchronizer
- Synchro-check
- Differential protection
- Power monitoring unit

The following diagram shows the complete protection functions that needs to be available in the generator protections IEDs to provide full protection to the generator,

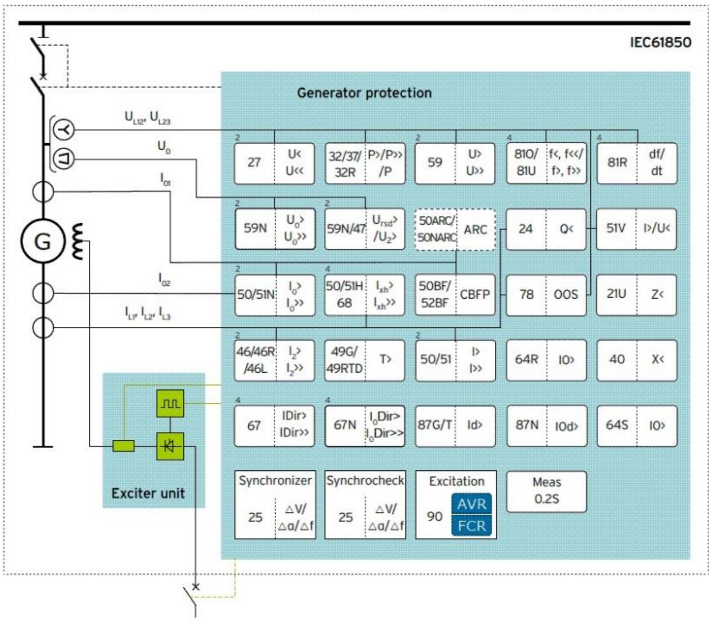


Figure 5.1 Generator protections function with ANSI numbers [12]

Excitation

The excitation system should provide following functions,

- AVR- Automatic voltage regulator
- FCR- Field current regulator
- Q- Reactive power control
- PF- Power factor control
- U>Ex- Over excitation
- U<Ex- Under excitation
- I-stator- Stator current limiter

Synchronizer

- U- Voltage
- f- Frequency
- Phase angle

IED Selection: The Generator protection AQ-G257 & Generator excitation AQ-GC30 has the capability to provide all the above-mentioned protection requirements, so this unit has been selected for generator protections.

5.2 Induction motor protection

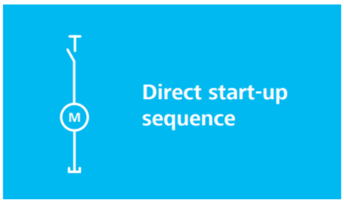
Then motor require following protection functions,

- Motor protection in general (Voltages and currents)
- Differential Protection (only used for large size motors)
- Start-up sequence control
- Power and Energy measurement

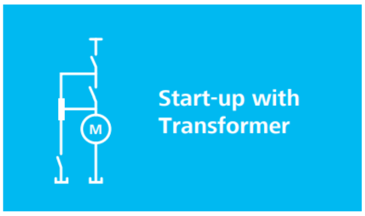
Motor starting sequence

Motor starting is the critical point which can be done by following methods,

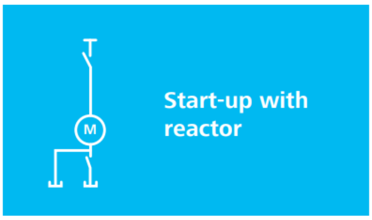
- Direct start-up:



- Start-up with Transformer:



- Start-up with Reactor:



The following diagram shows the complete protection functions that needs to be available in the Motor protections IEDs,

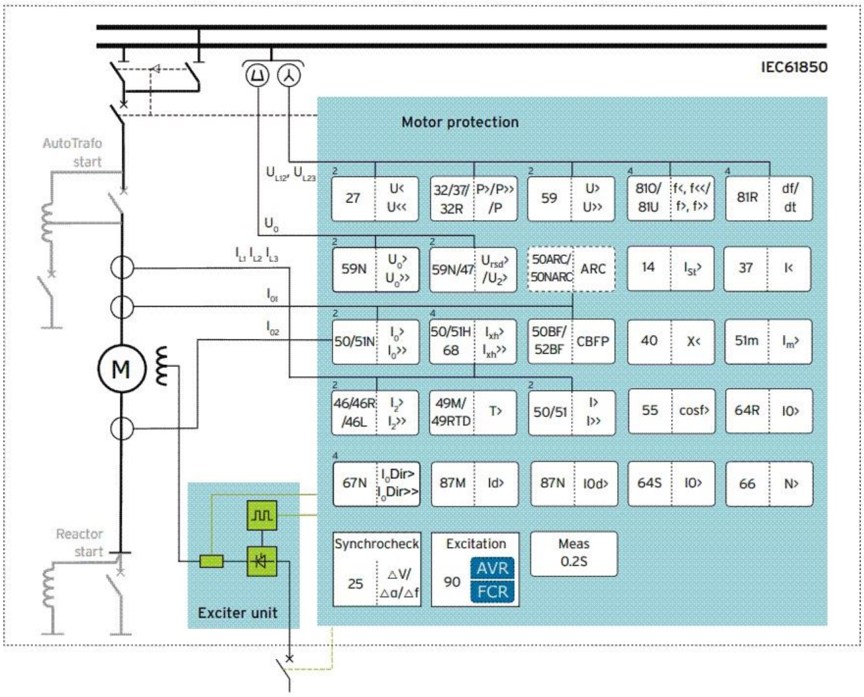


Figure 5.2 Motor protections function with ANSI numbers [12]

5.3 Transformer protection

- Transformer protections in general
- Over current protection
- Over voltage and undervoltage protection

- Over or under frequency
- Under impedance protection
- Transformer thermal overload protection
- Differential protection (main protection of the transformer)

Thermal overload protection:

This protection is used for power transformers thermal capacity monitoring and its protection. This function continuously monitors phases currents (including harmonics up to 31^{st}) instant values and calculates the set thermal replica status in 5ms cycles.

The basic operating principle of the thermal replica is based into that the nominal temperature rise is achieved when the protected object is loaded with nominal load in nominal ambient temperature. When the object is loaded with nominal load for time equal its heating constant tau (τ), 63% of the nominal thermal capacity is used. When the loading continues until 5 times this given constant the used thermal capacity indefinitely approaches to 100% but never exceeds it. With a single time-constant model, cooling of the object follows this same behaviour reversible to the heating when the current feeding is completely zero.

Transformer differential protection

Transformer differential is used for power transformer protection for two winding transformers and in some extent for three winding and two winding transformers with double outputs with summing application.
Transformer differential function is based into calculation of ingoing and outgoing current difference, e.g. the normal operating status of the transformer follows the Kirchhoff's current law, so the incoming currents must be equal to the outgoing currents in normal. If this is not the case, transformer has an internal fault which should be de-energized as soon as possible to avoid extensive damage to the transformer. Mostly can be said that if differential function operates the transformer which is faulty is going to be offline for a long time, if the fault is de-energized fast that can still save a lot of money since in most cases the transformer can be still repaired, and the cost is significantly lower than buying a new transformer.

5.4 Protection design for laboratory

In order to protect the laboratory model, we need IEDs for generator, motor and transformer. From the protection IEDs list, I have selected following IEDs.

- Generator protection AQ-G257
- Generator excitation AQ-GC30
- Motor protection, generator IED provides the same protection
- Transformer protection AQ-T257

The model diagram with the basic IEDs, CT and VT connections, and communication lines are represented in following figure,

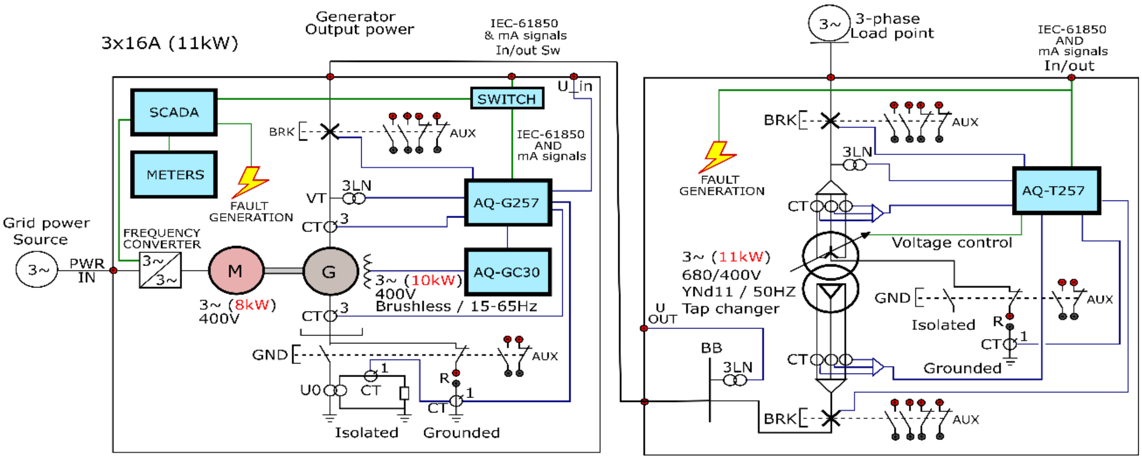


Figure 5.3 Laboratory module protection design layout

5.5 Arc protection design for laboratory

The Arc protection is the most advanced technology in the field of protection and getting famous in the market due to the minimum operation time then the conventional relays. Arc relays takes 5ms to send a trip command to the breaker to operate.
Arc protection devices are cheaper in cost and easy to do the commissioning as compare to the relays. It is composed of arc relays and sensors (point sensors and fiber optic sensors). The sensor detects the arc and make the arc relay to perform the tripping of breaker. There are different tripping criteria can be set on relays, it can be,

1. Light only tripping criteria (L>)
2. Light + current tripping criteria (L>+I>)
3. Light + pressure tripping criteria (L>+P>)

4. Optical fiber sensors
5. Infrared sensor (under development & testing phase)

The simplest configuration with the combination of pressure and light sensors with 2 arc protection relays as dedicated arc protection is shown here.

The yellow colour sensors work on (L>+P>) and blue one on (L>) only. In this application the breaker compartment sensors are selected as (L>+P>) so that the tripping should not takes place on breaker ON/OFF operations.

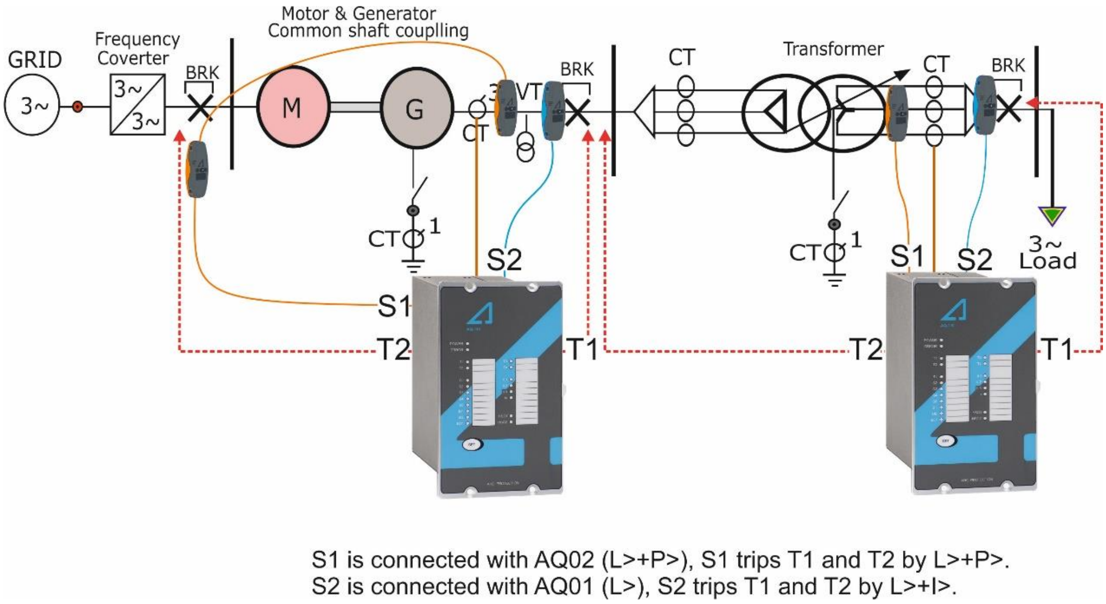


Figure 5.4 Laboratory module arc protection design

There is also possibility to use arc protection with conventional relays by selecting arc option card, but the number of sensor connections are limited in a card and selectivity in protection may be compromised but for small substations it’s a cheapest solution.

The arc protection system settings and configurations are easy as compare to the relays settings. Arc protections IEDs are provided with pre-tested schemes which can be selected on the back of the IED with a dip switch. There is only one set switch on the HMI to do perform set, re-set or new system configurations. The system is designed with self-supervision capability where all the arc IEDs communicates and monitor each other and the wirings. If there is any change in the system or problem occurs with the wiring, relay generates an error command.

6. COMMISSIONING, TESTING AND RESULTS VALIDATION

This chapter comprise of the commissioning of the protection system design for the laboratory. A test module contains all the protection relays needed for the laboratory protection such as generator commander, motor protection, transformer protection and some units for alarms. A dedicated arc protection with sensors also connected in the module.

First section shows the module pictures commissioned and second section explains the method to do the configuration of the relays. An AQtivate software is used to do the configuration. An AQviewer software is used for the disturbance analyser.

The relays testing is an important step in the commissioning process to check that the protection devices operates correctly and according to the setting written on relay. Here, Omicron device is used for testing, which can supply variable voltage, current and frequency as set by the user. It’s also possible to upload a complete disturbance into the testing device using ‘Advanced TransPlay’ which behaves as a real system on disturbance and injects all the parameters according to the disturbance curve.

Following tests are performed on one of the relays and test reports are also attached.

- Undervoltage
- Overvoltage
- Over current
- Over frequency
- Under frequency

Finally, there are two technical case which were analysed using the same methodology and attached with the conclusions and results.

6.1 Commissioning of protection system for laboratory

The electrical network of the laboratory is modelled using software techniques and got the disturbance data. Now, in order to test the disturbances, the real protection system module is commissioned below.
The lab protection module with all the necessary protections IEDs are shown here,

Generator commander:
AQ-G257 & AQ-GC30 [12]

Figure 6.1 Laboratory protection module panel

The upper section is connected to generator protection IED AQ-G257 and arc protection with some sensors. The lowest relays are for alarm indication or data measurements used for metering purpose only.

6.2 Laboratory relays configuration

To design the protection module panel, the relays are taken from the ARCTEQ RELAYS Oy. In order to do the relays configuration following software is used,

1. AQtivate software for relays configuration
2. AQviewer software for reading disturbance record

6.2.1 AQtivate software

AQtivate software tool is a program used for setting and making configurations for Arcteq AQ-200 series protection and control IEDs. Program uses a modern graphical interface and user-friendly. This software can be used for both reading and writing configurations and capable of reading the disturbance recordings from the device. These recordings can be further evaluated using AQviewer software. Settings are stored as a single “. aqs” file which includes all the user settable configurations (protection, measurement, communication, logics etc.). These “. aqs” files can be saved and stored on a hard drive. Configuration can be done offline and online

The relays are equipped with two RJ-45 ports, one in the front and one in the back. Both can be used for configuration and back port is for communication, as the front port has fixed IP address (192.168.66.9) whereas the back-port IP address can be configured of own and used for connection with SCADA.

AQtivate interface

Following figure shows the interface of the relay configuration software. When the relay arrives from the factory, it has all the functions on disable and can be enabled when needed. After connecting the relay with the computers through an ethernet port, respective IP address can be placed to connect it with the relay.
Once the device is connected, the interface will turn green and shows as below,

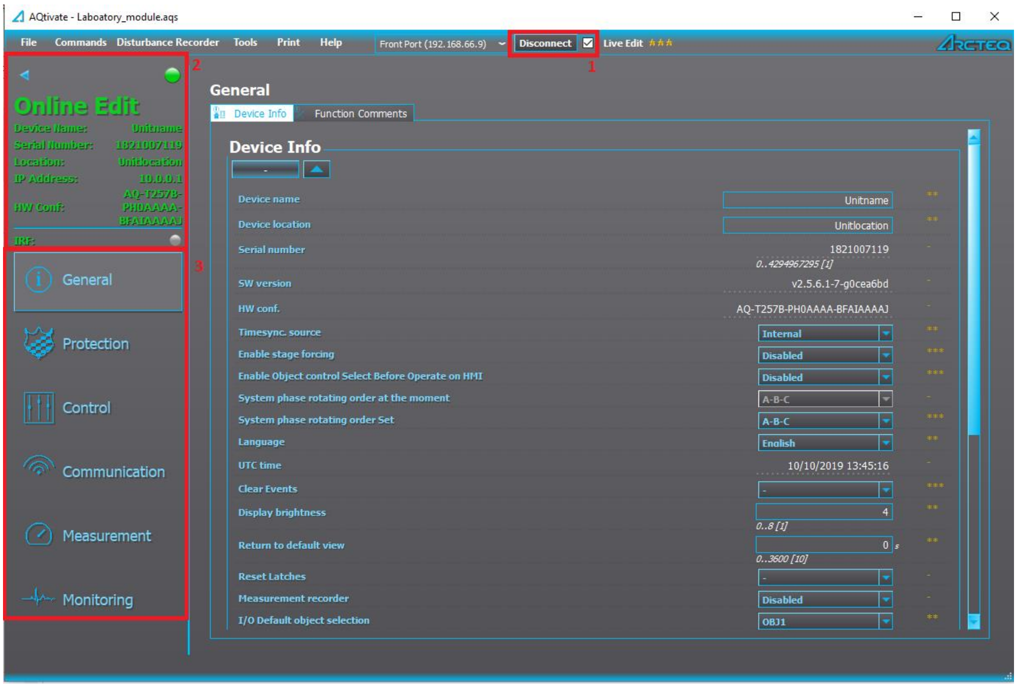


Figure 6.2 Relays configuration software interface (AQtivate)

Numer-1 is place where you connect/disconnect with the IED and PC.
Number-2 the green part shows that the IED is connected to PC and shows device name, serial number, location, IP address and HW configuration of device. It turns red if IED is disconnected.
Number-3 is the menus tabs, and each tab can be opened to do the configuration and it is divided in 5 sections, general, protection, control, communication and monitoring. This ease the configurator to find the relative option quickly. Same menu tab is also available on HMI of the IED. The functions appear according to the type of relay. Most of the relays has general function in common and some specific according to the relay type.

Uploading configurations:

Once you have written all the parameters data, you can give a command to write all the settings to the relay or select the specific as shown here, once all the settings are selected, press write, and it will transfer all setting in the relay.

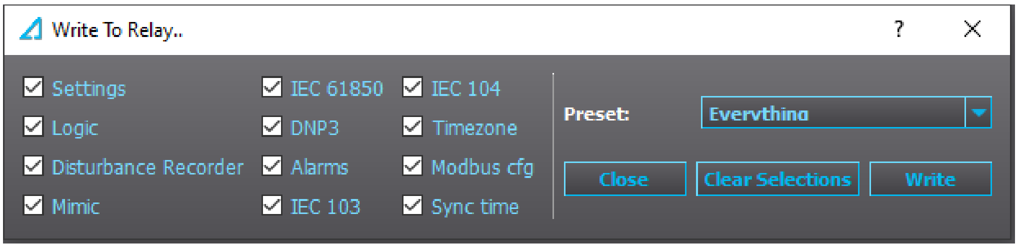


Figure 6.3 Relays configuration uploading to relay (AQtivate)

6.2.2 AQviewer (disturbance viewer)

AQviewer software is used to deeply view and analyse the disturbance which are downloaded from the relay or received through SCADA. Recordings are packed in COMTRADE files. The interface of AQviewer can be seen here in figure 6.4.

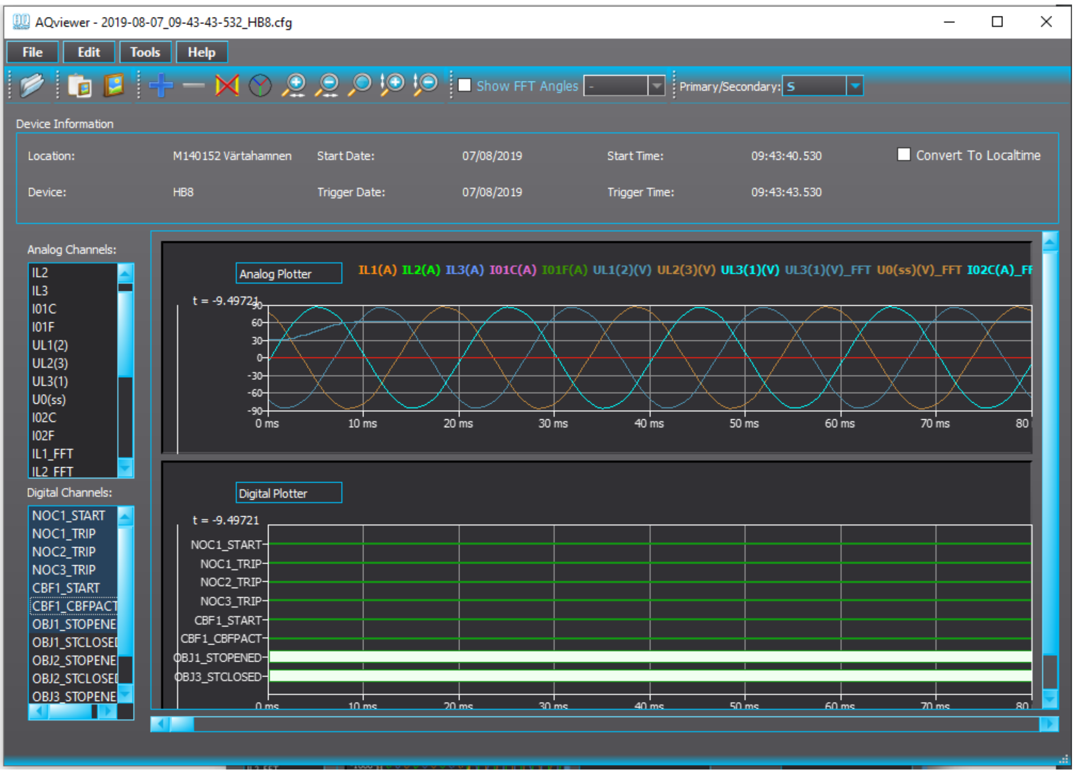


Figure 6.4 Relays disturbance reading software interface (AQviewer)

6.3 Testing and result validation

Testing Equipment (OMICRON CMC 356)

The relays are tested with the use of testing devise, here omicron, a universal testing device for the relays has been used. The CMC 356 is a computer-controlled test set for the testing of protection relays, transducers, energy meters and power quality analysers.

This device consists of 4 × voltages, 2 galvanically separated three-phase current outputs, DC supply, binary outputs and inputs [11].

Figure 6.5: OMICRON CMC 356 [11]

The following figure 6.6 shows the interface of the Omicron software where options are available to select the amount of current, voltage and frequency.

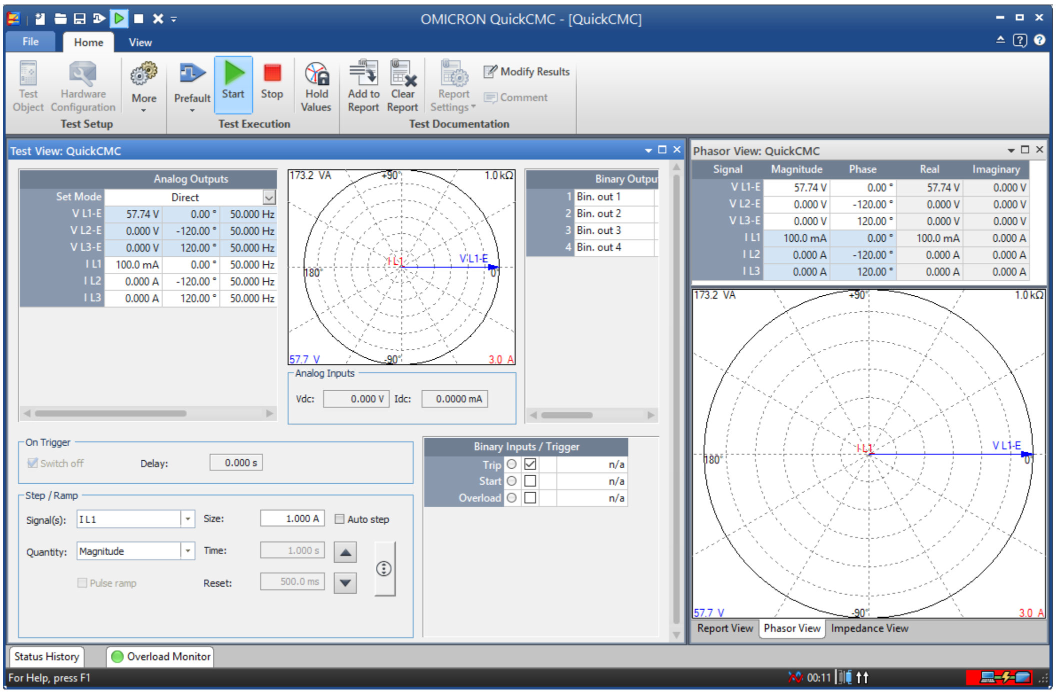


Figure 6.6: OMICRON CMC 356 interface

The relays parameters are set accordingly, if the applied quantities go out of the set limits, the relay devices will trip according to the delay time set settings.

Here are some base values used,

- Frequency f is 50Hz, if f<49Hz or f>51 consider as disturbance.
- U is 57.74 volts secondary side where U> is 110%Un and U< is 80%Un. when U<20% of Un, it blocks undervoltage tripping to differentiate between power off or undervoltage.
- I> 0.9In secondary side, it trips the over current protection.

According to the above settings some of the functions are tested with testing device and reports are attached below,

Under voltage test report

Here, the nominal voltage (Un) is 57.74 from the VT secondary and relays undervoltage settings are done as 0.8Un which means below 80% of Un is undervoltage, which is 46.2V. The voltage lower than this value considered as a low voltage and the relay will trip according to the set tripping delay. The low voltage (37.74V) is supplied and it trips in 36.9s after a set delay as seen in the following test report.

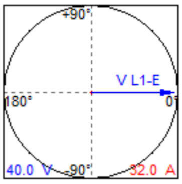
Title: Under Voltage (U<)

Fault Calculator:

Table Inputmode	Parameters (All values are secondary)			
Direct	V L1-E	37.74 V	0.00 °	50.000 Hz
	V L2-E	0.000 V	-120.00 °	50.000 Hz
	V L3-E	0.000 V	120.00 °	50.000 Hz
	I L1	0.000 A	0.00 °	50.000 Hz
	I L2	0.000 A	-120.00 °	50.000 Hz
	I L3	0.000 A	120.00 °	50.000 Hz

Generator Settings

V L1-E	37.735V	0.00°
V L2-E	0.000V	-120.00°
V L3-E	0.000V	120.00°
I L1	0.000A	0.00°
I L2	0.000A	-120.00°
I L3	0.000A	120.00°



Binary Inputs

Name	Slope	Time
Trip	0->1	36.906s
Start	1->0	n/a
Overload	1->0	n/a

Figure 6.7: Under voltage testing test report

Over voltage test report

Here, similarly the overvoltage U> is tested on relay. The settings for the over voltage are 1.1Un, which means above 110% of the Un (63.5V) is considered as over voltage. In the following test when 67.7 volts are supplied, the relay tripped within 20ms as seen in the following attached test report.

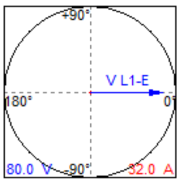
Title: Over Voltage (U>)

Fault Calculator:

Table Inputmode	Parameters (All values are secondary)			
Direct	V L1-E	67.74 V	0.00 °	50.000 Hz
	V L2-E	0.000 V	-120.00 °	50.000 Hz
	V L3-E	0.000 V	120.00 °	50.000 Hz
	I L1	0.000 A	0.00 °	50.000 Hz
	I L2	0.000 A	-120.00 °	50.000 Hz
	I L3	0.000 A	120.00 °	50.000 Hz

Generator Settings

V L1-E	67.735V	0.00°
V L2-E	0.000V	-120.00°
V L3-E	0.000V	120.00°
I L1	0.000A	0.00°
I L2	0.000A	-120.00°
I L3	0.000A	120.00°



Binary Inputs

Name	Slope	Time
Trip	0->1	0.020s
Start	1->0	n/a
Overload	1->0	n/a

Figure 6.8: Over voltage testing test report

Over current test report

This is the overcurrent I> test report, where nominal currents from the CT secondary is 1A and relay settings are set as 0.9In. Current above this value (0.9A) is considered as overcurrent. When 1A is supplied, the relays overcurrent protection trips in 0.6s.

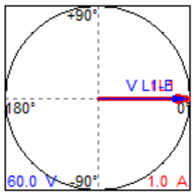
Title: Over Current (I>)

Fault Calculator:

Table Inputmode	Parameters (All values are secondary)			
Direct	V L1-E	57.74 V	0.00 °	50.000 Hz
	V L2-E	0.000 V	-120.00 °	50.000 Hz
	V L3-E	0.000 V	120.00 °	50.000 Hz
	I L1	1.000 A	0.00 °	50.000 Hz
	I L2	0.000 A	-120.00 °	50.000 Hz
	I L3	0.000 A	120.00 °	50.000 Hz

Generator Settings

V L1-E	57.735V	0.00°
V L2-E	0.000V	-120.00°
V L3-E	0.000V	120.00°
I L1	1.000A	0.00°
I L2	0.000A	-120.00°
I L3	0.000A	120.00°



Binary Inputs

Name	Slope	Time
Trip	0->1	0.602s
Start	1->0	n/a
Overload	1->0	n/a

Figure 6.9: Over current testing test report

Over frequency test report

Here, it's over frequency test report,

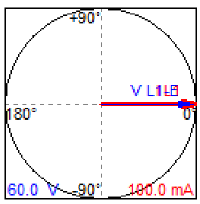
Title: Over Friquency (f>)

Fault Calculator:

Table Inputmode	Parameters (All values are secondary)			
Direct	V L1-E	57.74 V	0.00 °	52.000 Hz
	V L2-E	0.000 V	-120.00 °	52.000 Hz
	V L3-E	0.000 V	120.00 °	52.000 Hz
	I L1	100.0 mA	0.00 °	52.000 Hz
	I L2	0.000 A	-120.00 °	52.000 Hz
	I L3	0.000 A	120.00 °	52.000 Hz

Generator Settings

V L1-E	57.735V	0.00°
V L2-E	0.000V	-120.00°
V L3-E	0.000V	120.00°
I L1	0.100A	0.00°
I L2	0.000A	-120.00°
I L3	0.000A	120.00°



Binary Inputs

Name	Slope	Time
Trip	0->1	0.102s
Start	1->0	n/a
Overload	1->0	n/a

Figure 6.10: Over-frequency testing test report

The system nominal frequency is set as 50Hz, with the deviation of ± 0.02f which is (49Hz≥f≥51Hz) considered as over or under frequency. In the above attached report, the system is supplied with 52Hz frequency, the relay over frequency protection trips in 0102s.

Under frequency test report

Here, it's under frequency test report, when the system is supplied with 49Hz frequency, the relay detects it as an under frequency and trips the relay in 0.139s with under frequency protection function as seen in following report.

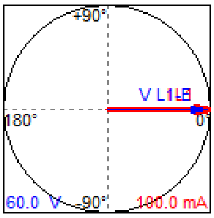
Title: Under Friquency (f<)

Fault Calculator:

Table Inputmode	Parameters (All values are secondary)			
Direct	V L1-E	57.74 V	0.00 °	49.000 Hz
	V L2-E	0.000 V	-120.00 °	49.000 Hz
	V L3-E	0.000 V	120.00 °	49.000 Hz
	I L1	100.0 mA	0.00 °	49.000 Hz
	I L2	0.000 A	-120.00 °	49.000 Hz
	I L3	0.000 A	120.00 °	49.000 Hz

Generator Settings

V L1-E	57.735V	0.00°
V L2-E	0.000V	-120.00°
V L3-E	0.000V	120.00°
I L1	0.100A	0.00°
I L2	0.000A	-120.00°
I L3	0.000A	120.00°



Binary Inputs

Name	Slope	Time
Trip	0->1	0.139s
Start	1->0	n/a
Overload	1->0	n/a

Figure 6.11: Under-frequency testing test report

6.4 Laboratory module test for real application

The following cases were solved using same methodology as developed in this thesis work. Case 1 is solved using the laboratory module and case 2 is solved by creating another similar model using arc protection relays.

6.4.1 Case 1: Relays detection capability over high impedance faults

Problem:

Detection of high impedance faults for PG&E corporate (pacific gas & electric company) San Francisco US to minimize wildfire.

The following SLD (Single line diagram) shows the typical example of a network system with 500 miles of distribution network with overhead (OH) and underground (UG) cable network in a remote rural area given below in figure 6.12.

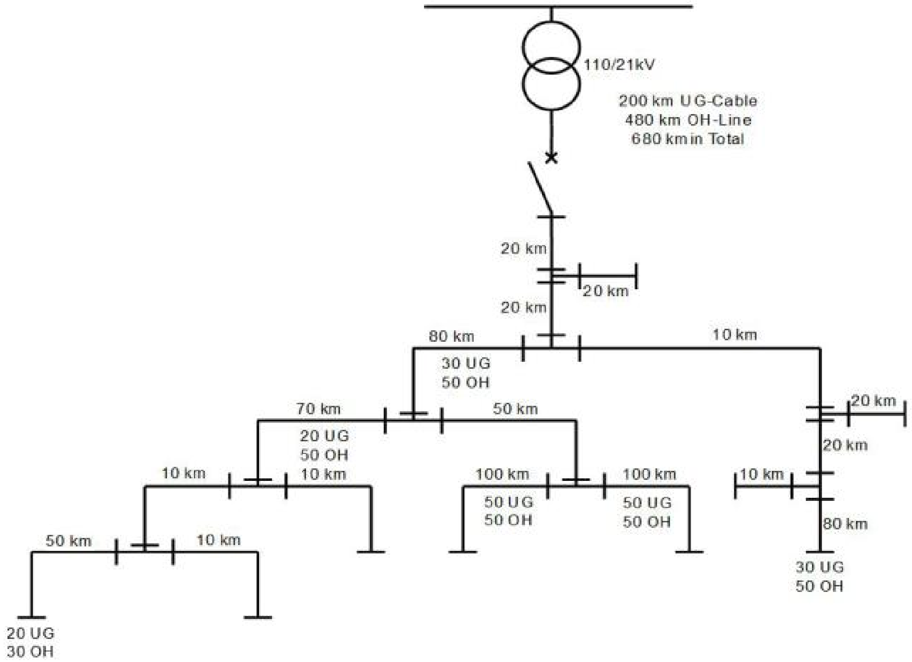


Figure 6.12: PG&E substation SLD of 500miles distribution network

The above given network was simulated with all the provided data from the customer and obtained a model as shown in the following figure 6.13.

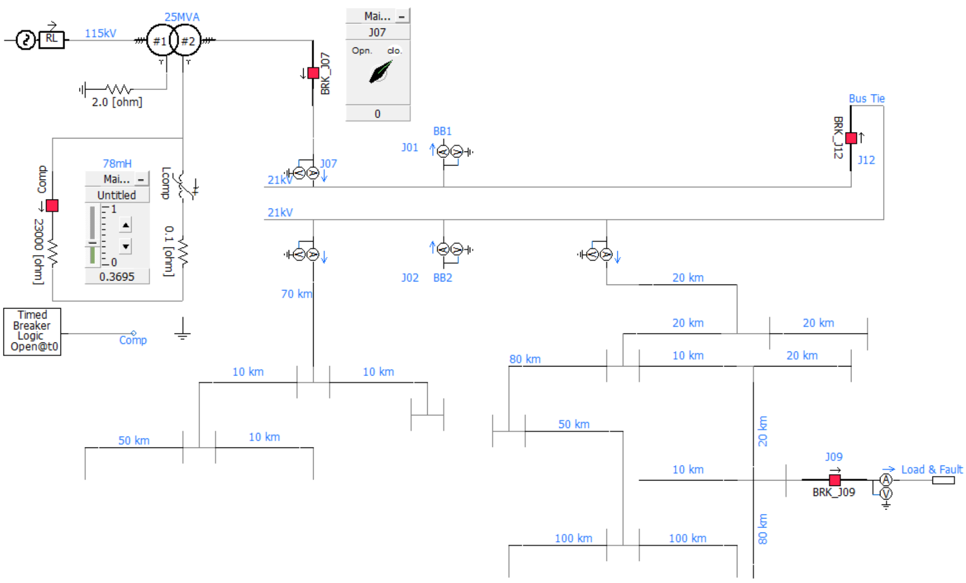


Figure 6.13: PG&E substation layout simulation diagram

Fault analysis:

The high impedance faults were applied on different parts of the network. One of the fault types is attached here. Curves of all the parameters when a L-L-G fault occurs on the system with 30k ohms fault resistance is shown here in figure 6.14.

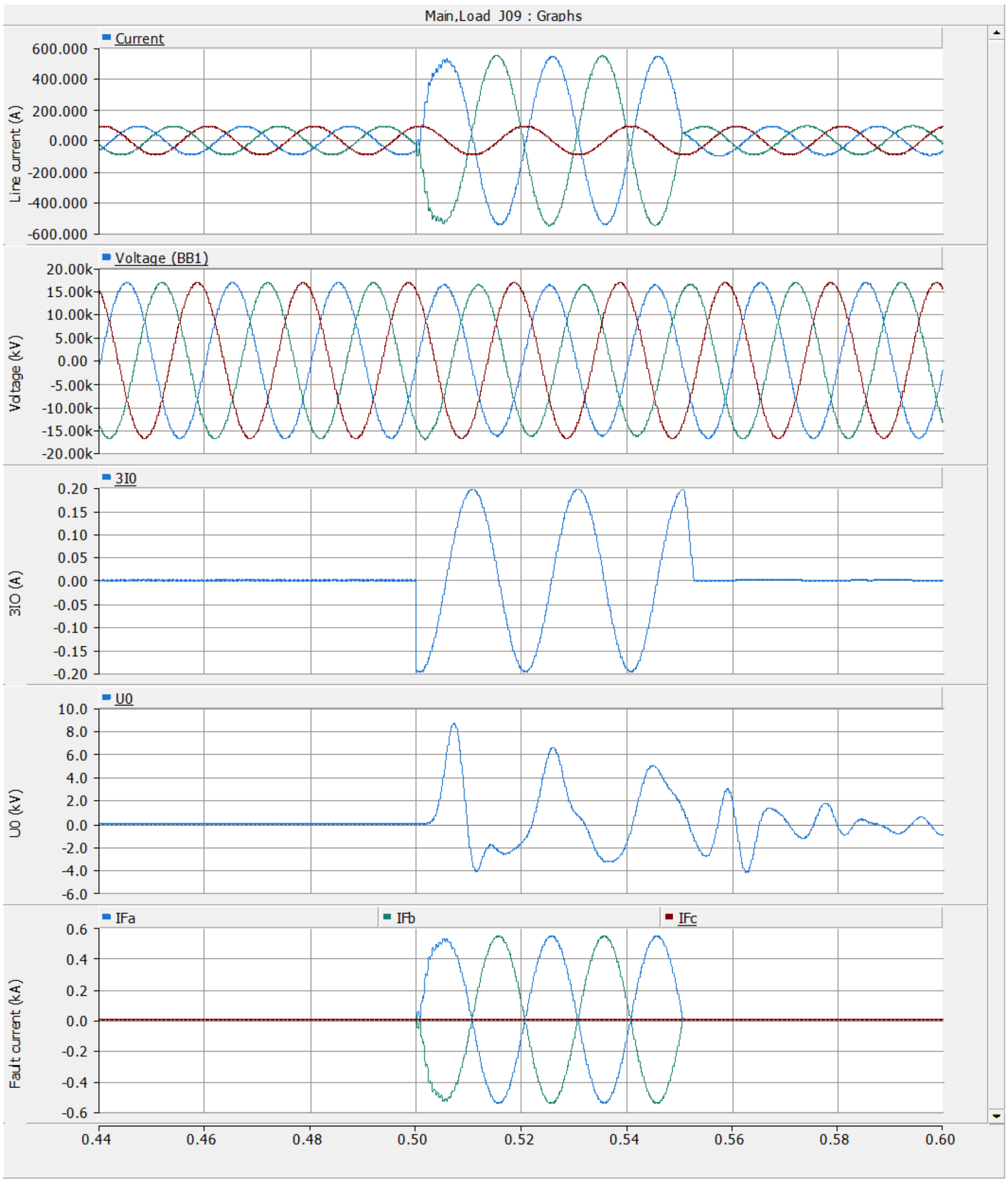


Figure 6.14: PG&E substation simulation curves

Results:

Omicron test current curve from the report shows the ARCTEQ relays can detect high impedance faults when the substation transformer neutral is compensated grounded. This curve has been tasted and verified on feeder protection relay.

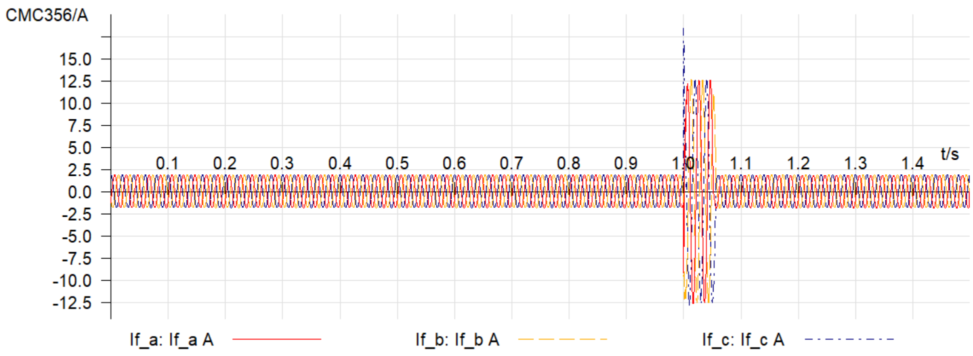


Figure 6.15: PG&E substation omicron test curve

6.4.2 Case 2: Arc protection mall operation of CBFP

Problem:

Testing of arc protection failure at Tenaga Nasional Berhad (TNB), on the largest utility in Malaysia. The following figure shows the substation single line diagram where the fault took place is shown below in figure 6.16.

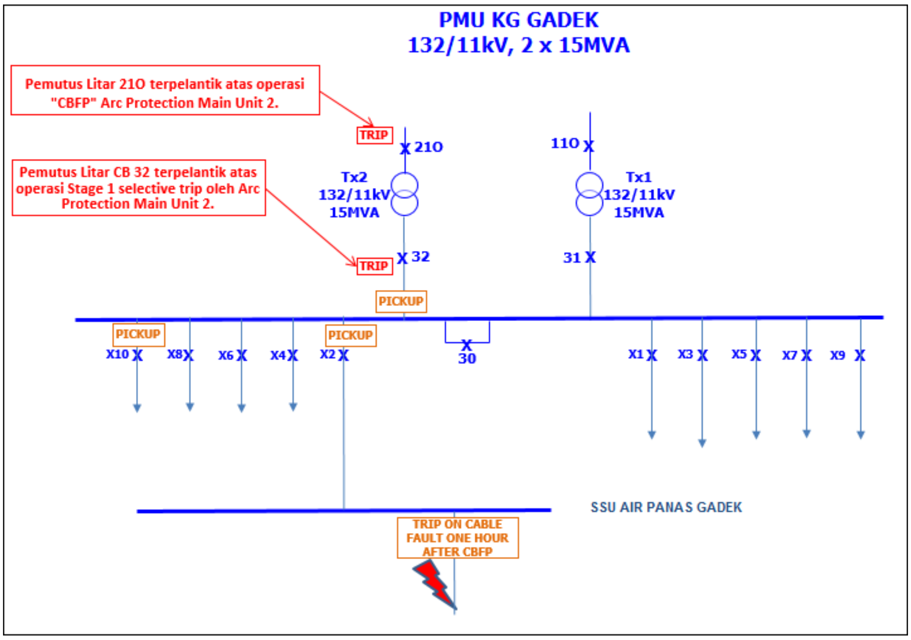


Figure 6.16: TNB case network

Arc protection tripping criteria is light and current (L>+I>), but here unit trips on current only. One hour after CBFP, there is a cable fault in the outgoing feeder.

The disturbance curve provided by the customer is shown here,

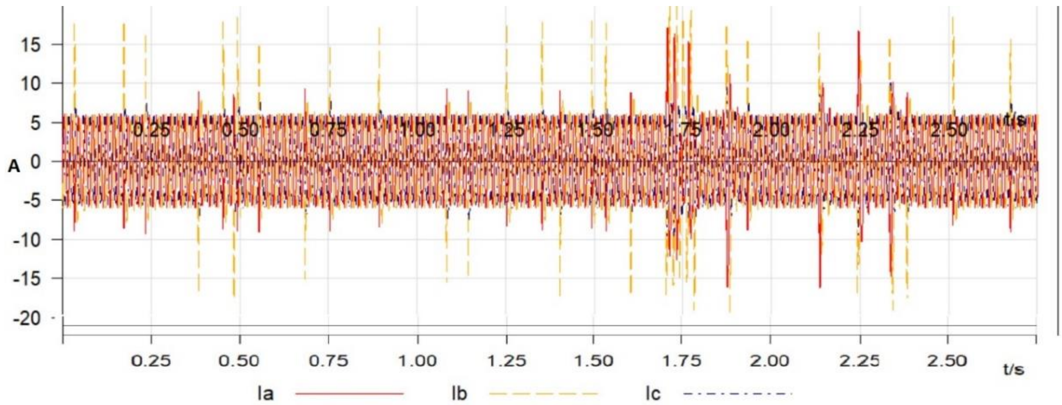


Figure 6.17: TNB disturbance from customer

Test module and disturbance analysis:

In order to investigate the problem and find a reasonable solution, following module commissioned as a similar replica of the TNB substation. The test arrangement can be seen below, an external oscilloscope was also used to record various pulses/signal during the testing.

Figure 6.18: TNB testing module

Figure 6.19: TNB disturbance analysis

On a closer look it has been observed that the system faces large number of intermittent faults, the fault magnitude and time is not enough for relays (other than arc) in TNB network system to detect those faults and instead it makes a false tripping from arc protection. So, in order to detect the root cause, testing unit injected the small part of the disturbance into the system and came up with following conclusions,

Following are the test setting and report generated from the test device.

Test Settings

Data source:

Path: C:\USERS\RAJ.KUMAR\DESKTOP\TNB CASE\CB32\2\DR\
File: 07.09.2019 14.47.24.360 DISTURBANCE.000.CFG
Info: MiCOM P123 BXXXXXX V11.D

Analog Output:

	Name	Scale	Min	max
I L1	Ia	2.00 %	-16.38 A	17.06 A
I L2	Ib	2.00 %	-20.00 A	20.25 A
I L3	Ic	2.00 %	-10.10 A	10.41 A

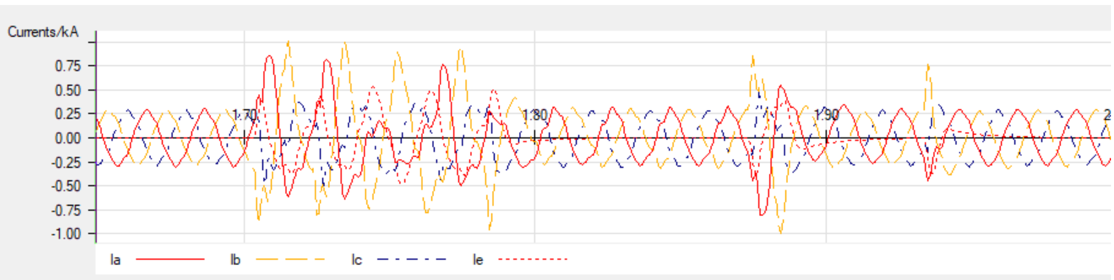


Figure 6.20: TNB omicron test report

Following curve is the oscilloscope record of our testing unit when the arc relay trips on intermittent fault.

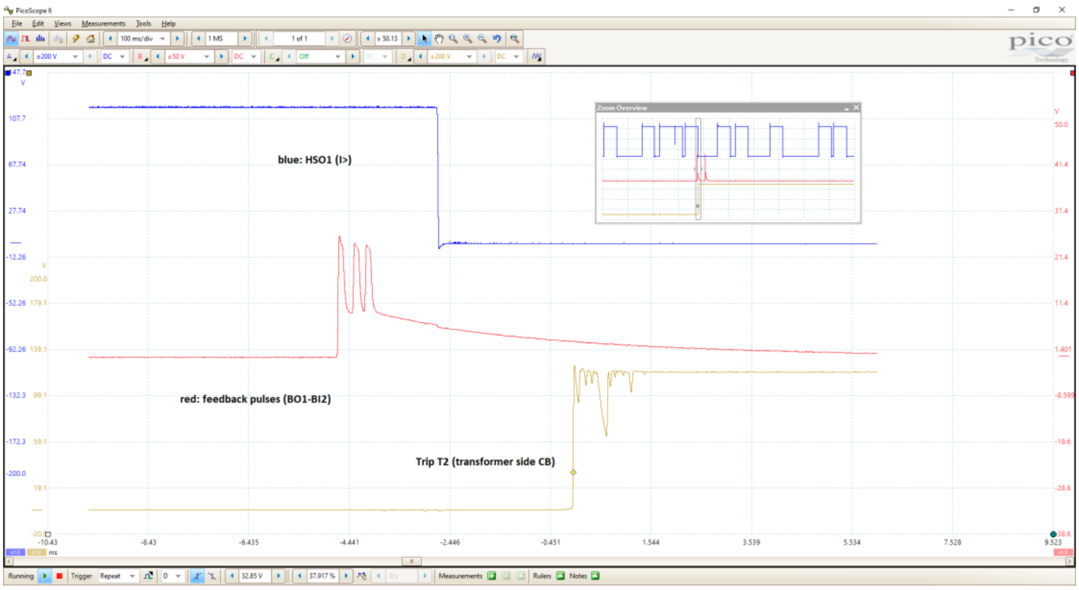


Figure 6.21: TNB arc device tripping signals record

TNB case findings:

The arc protection unit trip over intermittent fault due to the feedback pulse (Binary input BI1) signal which monitor the system self-supervision and due to intermittent faults for longer time in the system, the self-supervision pulse system considers the system on fault and thinks that the beaker is not operating and activate trip T2 command as a circuit breaker failure protection (CBFP).

As explained in the description, after 1 hour of CBFP the outgoing feeder cable tripped on fault. Which shows that there are continuously intermittent faults generated by the system and ignored by the relays, which ultimately degrades the network components like the cable end and weaken network parts and finally leads to a permanent system fault as appeared a cable fault in this case.

TNB case solution:

1. The intermittent faults are hazardous to the system for longer time and leads to the big faults or system damage, so either the old relays should be replaced with the new advanced one or use a relay to detects the intermittent faults.
2. Arcteq feeder protection IED AQ-F215 is equipped with the intermittent earth fault protection. It is patented with the high accuracy measurement of 0.2s and sampling frequency of 3.2kHz is capable to detect and isolate all intermittent faults. AQ-215 IED can be used in the system.
3. The Arc relays system software updates and modifications can be done in self supervision system to remove CBFP tripping.
4. CBFP option can be kept on disable

7. CONCLUSIONS AND FUTURE WORK

The study of theoretical literature work, power system simulation design and modelling, protection system design and number of experiments on real cases brought great ideas to deal with the complex network systems. PSCAD software has an important role to produce the simulation models and to interpret the results based on it. The software tool is easy to use and provide enough data to deal with technical problem which are impossible to achieve with the real system such as producing faults or disturbances. Fault are natural and inevitable, but with the best protection scheme and equipment, it is possible to protect system from big damages. With paper calculations one can calculate and design a system but with the advanced software it is possible to visualise such system as some of the examples are done in the thesis work.

The major work includes the combinations of simulated networks model with the real protection equipment. An especial feature used to convert the simulated results in a format which is being recognized by the testing devices like omicron as well as the protective IEDs. The simulated disturbance injected through the testing device works similar as the IEDs connected with the system on disturbance, which helps to test, verify and add advanced feature in IEDs before using it in the system. The laboratory protection panel included with arc protection is ready to be used for all the application. It will be used to educate customers, partners and protection learner with relays configurations, testing and commissioning of protection system at Arcteq academy. Advance network issues and complex protection testing can also be performed using this panel. During thesis work development, same technique used to solve 2 complex issues from company partners therefore, it is considered as a very helpful tool for next upcoming challenges.

7.1 Future work

The future task includes the development of laboratory to move the system more towards the real network by using laboratory scale generator, motor, transformer, transmission lines and loads.

- The future work is to develop a complete laboratory will all the power system equipment which are modelled here.
- To develop methods to produce faults on a real system such as high impedance faults.
- Advance control system to monitor the laboratory remotely with SCADA.
- Advance sensors development to get the real time system condition monitoring.
- A build laboratory to test future applications and practical issues.

REFERENCES

[1] P. G. McLaren, K. Mustaphi, G. Benmouyal, S. Chano, A. Girgis, C. Henville, M. Kezunovic, L. Kojovic, R. Marttila, M. Meisinger, G. Michel, M. S. Sachdev, V. Skendzic, T. S. Sidhu, and D. Tziouvaras, " Software Models for Relays", IEEE Transactions on Power Delivery, Vol. 16, No. 12, April 2001, pp. 238-45.

[2] Sandro G. Aquiles Perez, Modelling Relays for power system protection studies July 2006.

[3] RTDS Technologies https://www.rtds.com/about-rtds-technologies/.

[4] Mark Brown, Ramesh Balakrishnan, & Leslie Hewitson Practical Power Systems Protection, Elsevier Science & Technology, 2004. ProQuest Ebook Central, https://ebookcentral.proquest.com/lib/tampere/detail.action?docID=232138

[5] Emil Anthonsen Dyrstad, Relay Lab at NTNU (Norwegian University of Science and Technology) June 2014.

[6] Arcteq Relays AQ-250 series, Instruction manual AQ-G257 Generator protection IED, https://arcteq.fi/wp-content/uploads/2019/06/AQ-G257-Instruction-manual-2.00EN.pdf

[7] X. Q. Tian et al., "Simulation and Analysis for Current Transformers with DC Bias and Remnant Flux", Advanced Materials Research, Vols. 765-767, pp. 2430-2434, 2013.

[8] Cai Jiong, Wang Jimei, using a parallel resonance circuit to measure time-current characteristics of high voltage current-limiting fuses. Published in: 2007 8th International Conference on Electric Fuses & their Applications10-12 Sept. 2007. Print ISBN: 978-2-84516-363-8 INSPEC Accession Number: 9766010 DOI:10.1109/ICEFA.2007.4419959 IEEE Clermont-Ferrand, France.

[9] Arcteq Relays AQ-250 series, Instruction manual AQ-F255 Feeder protection IED, https://arcteq.fi/wp-content/uploads/2019/06/AQ-F255-Instruction-manual-2.00EN.pdf

[10] Ogar, V.N., Abara, D.N., Akpama, E. J. Symmetrical and Unsymmetrical Faults Analysis: using Nigeria 330-KV grid as case study, Department of Electrical/Electronic Engineering Cross River University of Technology, CRUTECH. Calabar, Nigeria.

[11] Omicron CMC 356, Universal relay test set and commissioning tool. https://www.omicronenergy.com/en/products/cmc-356/

[12] Arcteq Relays AQ-250 series, Instruction manual generator-motor commander https://arcteq.fi/wp-content/uploads/2017/11/Generator-and-Motor-Commander_-Brochure-1.1_EN.pdf

THE END